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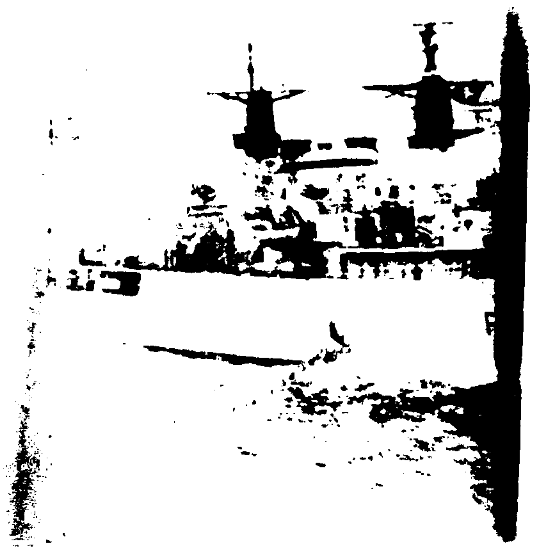

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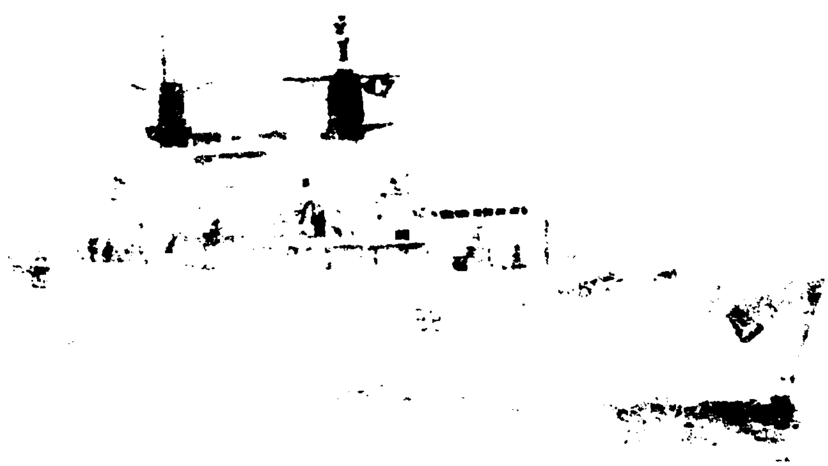

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Volume 1

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d. Hardware and software should not be developed simultaneously, software should be developed first, then hardware found to meet the identified need.

e. The time response to mircroprocessor based systems when working in real time needs careful specification and management.

f. Great care is needed in providing adequate diagnostic facilities to ensure such systems are maintainable.

APPLICATIONS

At this point in time we have now arrived at a system design philosophy based on distributed digital microprocessors. The system to be produced by Vosper Thornycroft Controls for the Type 23 Frigate will be based on the INTEL 8086 processor. It is our policy to hold a period of shore based evaluation at RAE (West Drayton) prior to the system being set to work in the first ship of the class.

This evaluation at West Drayton will of course utilise digital processors to simulate this ship machinery package. It will form one of the milestones in the implementation of digital technology into the RN machinery package and will give design feedback prior to shipborne setting to work and trials, which inevitably are some time away.

It has been evident during the design process for these systems that the implementation of the new technologies has overcome the natural resistance to change from methods which have apparently worked well in the past and the suspicion of that invisible control mechanism called software. These attitudes have had a significant influence on the end system in that the Type 23 machinery control and surveillance systemstill contains large quantities of dedicated circuits in parallel with digital data links. The current configuration does not optimise the utilisation of digital technology but is a first step in the transition from a total analogue technology to a software controlled digital one. The control and surveillance system depends ultimately upon the transducer on the plant which in turn feeds the on-plant controllers. Historically, local control panels are based upon analogue technology and this necessitates special interfacing electronics if the shipborne system is to be digitally based, and in some cases separate packaging with obvious increased costs. Utilisation of the digital based local control panel facilities with data link capability is a self evident solution and several such units are currently under detailed assessment. Although confident of success, we have some reservations regarding the ability of the units to meet the availability, reliability and maintainability targets and the effect of some failure modes. In the latter case we have traditionally trusted such devices with a large measure of plant protection facilities and need to gain some confidence that our trust in them is still well placed. Again later this week some further exposition of work in this area will be given.

In general we find that the solution of the control problem is less difficult than the solution of the surveillance needs. The current aim to reduce manpower in ships immediately impacts upon the design implying an increase in automatic surveillance and improvements in man machine interfaces. Efficiency in design and acceptance of new technologies have to compensate for the reduced numbers in the watchkeeping complement.

In the Type 23 Frigate the watchkeeping numbers in the cruising state has been reduced by 50% with reference to the Type 22 Frigate. As a result of this reduction, the number of parameters under surveillance in the ship control centre has increased by 500%. This increase results from the use of a centralised presentation to compensate for the reduced numbers of roundsmen. Previous design consisted of dispersed equipment which makes them surveillance manpower intensive.

This massive increase in surveillance requirements can be met in an ideal manner by the use of data collection units and digital data links. The new technology can match the results of manpower reductions in this area. I would submit that digital electronics offer the only cost-effective solution to a problem of this magnitude and as demands for the associated topic of condition based monitoring of equipment, increasing sophistication will result. However, the cost of electronic equipment is still falling and this is leading to change of priorities among the procurement agencies of such systems. By way of example, transducer costs now exceed those of electronics in surveillance systems focusing attention in their direction. Furthermore the cost of production is falling with no change in the cost of development, indeed in many instances the cost of development for software based products can be expected to rise. This often necessitates a change in emphasis on the procurement route.

MAN MACHINE INTERFACE

Where does the man fit into the proliferation that new technology now offers? Such a radical change in terms of maintenance loading presents a considerable challenge to the established manning structure associated with our ships. It is reasonable to expect any engineer to be able to maintain systems ranging from gas turbines, shafting, diesel engines and chilled water pumps through to complex microprocessor based systems? The answer is not known at this point in time. Clearly the training task is of major importance as is the need to build into systems good diagnostic facilities. We are attacking both these areas vigorously but will it be enough? Clearly we are conscious that other Navies have created separate specialists or have allocated responsibility for new generation control systems to weapon specialist areas who are familiar with such electronic systems already. It will be some time before we in the RN are aware of the success or otherwise of current manning and service branch policies.

Thus, as far as shipwide systems are concerned, we are currently in the midst of a period of consolidation and confidence building having taken the step from analogue to digital systems. Sight has not been lost of the fact that man and machine are themselves essentially analogue in nature as illustrated by the probable propulsion panel for the Type 23 from which the absence of digital display devices is perhaps surprising in a system based on digital electronics.

Before addressing what the future may hold, I would just like to mention one application of a read only memory which has been integrated into the existing ships analogue control systems. It takes the form of look-up tables held in EPROM allowing the facility to actually tailor a schedule to each ship. I hasten to add that this is not the intention, a standard optimised schedule will be provided, however this facility allows considerable flexibility in coping with variations in ship classes or variants of engine design.

FUTURE TRENDS

Now to finish we shall have a peep into the future. I believe as we learn more about the enormous potential of digital technology its applications will increase in the machinery control and surveillance field.

The industrial base of Great Britain involved in microprocessor technology has burgeoned with considerable speed over the past 5 years. As we now tend to follow commercial advances rather than lead them, it is inevitable that control solutions using digital technology will be offered for future requirements for ships; as they are in a multitude of industrial applications from steel rolling mills to computer aided design.

Intelligent knowledge based systems are being vaguely addressed for consideration as an adjunct to secondary surveillance with particular reference to condition based monitoring.

The man machine interface will benefit from advances in graphics packages, colour and speed of presentation compatible with the operator's needs. The applicability of touch sensitive displays and buttons in lieu of levers are not a few areas worthy of attention.

Distributed control and surveillance packages around the ship will be inter-connected via the true bus structure with the capability of ship control being exercised at any access point from bridge wings to steering flats. However, such a bus expansion must not reduce the reliability of the system as a whole. A fundamental fact concerning data rates applicable to machinery control and surveillance is that they are less than one tenth of combat systems but the acceptable error rate is considered more stringent by a factor of at least 1000.

It is my assertion that the sensible application of digital technology to machinery control and surveillance systems will achieve economically the goal of efficient control and surveillance of the propulsion and auxiliary package with a considerable saving in manpower and cost.

There, gentlemen, I hope I have whetted your appetite for the presentations which follow and stimulated you for the remainder of the week.

	UNITS SOLD	FUNCTIONS (BILLIONS)
MAINFRAME COMPUTERS	2,000	0.1
MINICOMPUTER	20,000	0.2
MEMORY	—	200
POCKET CALCULATORS	30,000,000	100
WATCHES	10,000,000	10
	TOTAL	310

FIGURE 1a.

DIGITAL INTEGRATED CIRCUIT SALES - 1976

Source: University of Bristol

	UNITS SOLD	FUNCTIONS (BILLIONS)
COMPUTERS	100,000	10
MEMORY	—	6,000
CALCULATORS	30,000,000	1,000
WATCHES	20,000,000	400
GAMES	10,000,000	1,000
CARS	10,000,000	2,000
	TOTAL	10,000

FIGURE 1b.

ESTIMATED DIGITAL INTEGRATED CIRCUIT SALES - 1985

Source: University of Bristol

FIGURE 2 PROPULSION PANEL 'A' INDICATES LEVERS

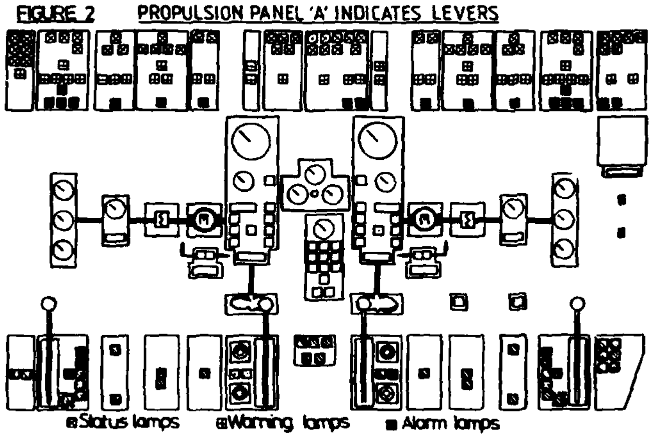
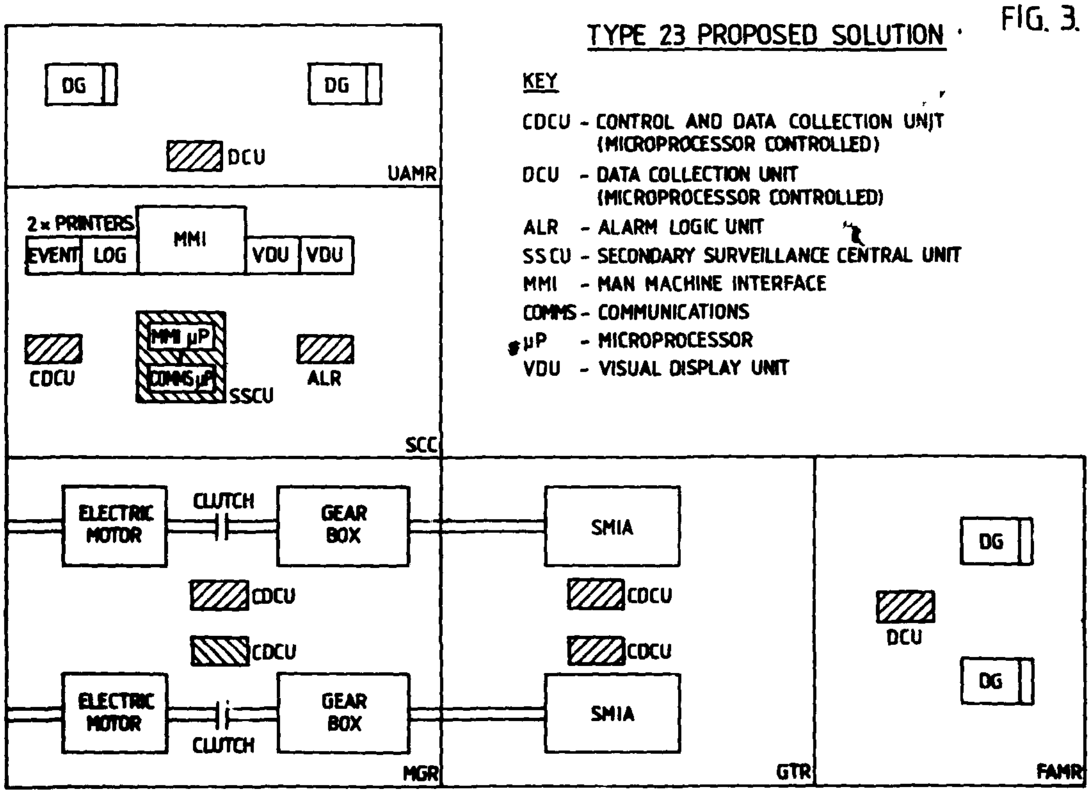


FIG. 3.

TYPE 23 PROPOSED SOLUTION



KEY

CDCU - CONTROL AND DATA COLLECTION UNIT (MICROPROCESSOR CONTROLLED)
DCU - DATA COLLECTION UNIT (MICROPROCESSOR CONTROLLED)
ALR - ALARM LOGIC UNIT
SSCU - SECONDARY SURVEILLANCE CENTRAL UNIT
MMI - MAN MACHINE INTERFACE
COMMS - COMMUNICATIONS
µP - MICROPROCESSOR
VDU - VISUAL DISPLAY UNIT

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TECH MEMO NAV. ENG. 1029 (M)

U.S. NAVY CONTROL SYSTEMS OVERVIEW

by George E. Holland
Naval Sea Systems Command

ABSTRACT

This paper introduces the papers being given at the 7th Ship Control Systems Symposium by representatives of the U. S. Navy. It discusses developments in machinery plant control systems as related to Navy policy and gives some personal views of the author.

INTRODUCTION OF PAPERS

My purpose is to introduce the papers which will be given at this symposium by people representing the U. S. Navy. While not a coordinated group, these papers do give a sampling of the various ways controls technology is being examined and applied by engineers in different parts of the naval shore establishment. Altogether, eight other papers will be given by my colleagues from naval engineering centers on the east and west coasts of the United States.

Six of these papers, which are research and development (R&D) oriented, discuss some interesting ideas and developments in navigation and directional control. The authors of these papers are Mr. James A. Fein and Mr. Thomas L. Moran of the David Taylor Naval Ship Research and Development Center, Carderock, Maryland, Dr. G. J. Dobeck, Mr. L. F. Walker, and Mr. D. C. Summey of the Naval Coastal Systems Center Panama City, Florida, and Prof. G. J. Thaler, and LT C. Garcia, USN of the Naval Postgraduate School, Monterey, California. Their papers deal with the use of controls technology both as an innovative design tool and as a direct application to the control of underwater vehicles and surface ships.

The R&D oriented paper by Mr. Herman Williams, of the Navy Personnel Research and Development Center, San Diego, presents some thoughtful ideas on the partnership between the operator and the computer which is needed for monitoring the condition of a machinery plant, and for taking effective corrective action when required.

The last paper deals with application rather than R&D. This paper by Mr. Ronald Benjamin, of the Naval Sea Systems Command in Washington, D.C., discusses the recent design of a digital, distributed machinery plant control system for a gas turbine driven surface ship. In this connection is it significant to note in passing that although there are several classes of steam ships in the fleet, some of these with automated plants (or, to be more exact, central control systems), a decision made earlier this year seems to presage the eventual end of steam propulsion in the U. S. Navy. Two new auxiliary ships, both updated repeat designs of steam ships built about fifteen years ago, will be fitted with gas turbine propulsion. While distressing to some who are saddened at the propect of facing the end of perhaps a more romantic era, this shift to gas turbines can be justified on the basis of cost (acquisition and life cycle), shipboard maintenance requirements and, possibly, manning. In suggesting this possible demise of steam, I am not forgetting the

Rankine Cycle Energy Recovery (RACER) system we have in development, and which can be added to a gas turbine plant to make it combined gas turbine and steam (COGAS). The steam for the steam turbine in this case is generated using waste heat, and this is not in any sense a conventional steam plant.

In addition to the papers from America which are being given at this Symposium by Navy personnel, there are several by representatives of private industry. Taken all together these papers indicate the diversity of thought and action by both government and private industry on ship control systems and associated problems, very much in keeping with the theme of the Symposium.

POLICY ON MACHINERY PLANT CONTROL SYSTEMS

Out of fleet experience, management perceptions and recent design projects, some guidelines or policies have evolved in the Naval Sea Systems Command, the Navy's ship design center, for the design of machinery plant control systems. The guidelines are:

1. Automate only that which is necessary.
2. Provide manual backup for automatic control.
3. Use standard components.
4. Provide remote monitoring only as necessary to detect credible casualties, and to allow intelligent use of the control provided.

The aim of the first guideline is to keep the control system from being unnecessarily complex. Simplicity has the benefit of enhancing reliability, plus reducing dependence on highly trained electronics specialists who can be difficult to retain. It has, in my opinion, the added advantage of keeping the watchstanders more actively involved in plant operation, and therefore more alert; casualties will be either prevented or dealt with swiftly and with the confidence born of experience when they do occur. Even though eventually we may install control systems which allow us to eliminate engineroom watchstanders altogether (and I know this is done commercially), we are not there yet in the Navy. Before this could happen, an entirely new concept of ship operation would have to be adopted. Recognizing therefore that watchstanders will be with us for a while, our experience is such that a moderate level of operator participation is essential to avoid boredom.

The second guideline is in a somewhat conservative vein, as is the first, but certainly, I believe, a prudent measure for a ship of the Navy.

The third guideline, theoretically at any rate, simplifies logistical support, but this may actually cause acquisition costs to be higher than they might otherwise be. Because of the rapid technological changes which are occurring, I think that this is one guideline which should be applied with extra care.

The fourth guideline is almost a corollary of the first. However, I have put it separately because it has proven to be a valuable rule of thumb for identifying signals necessary for remote operation and those needed only for local operation and maintenance.

PERSPECTIVE ON MACHINERY PLANT CONTROL SYSTEMS

At the Fifth Ship Control System Symposium in Annapolis, I gave a paper with Commander Eugene Fitzpatrick entitled "Automation - Salvation or Delusion."(1) That paper was based on a study, by Commander Fitzpatrick, of Machinery control in the Navy in the 1960 to mid 1970 timeframe, and we came down a little on the side of delusion. Six years later, touched with whatever wisdom comes with age, and although conscious of the ever present threat of delusion, I am most encouraged by the development of digital distributed systems, and am pleased to report a definite tilt this time toward salvation.

I find it interesting to note the developments and advancements in machinery plant control systems which have taken place, over the course of several ship control systems symposia, in the various participating nations. To be sure there have been differences in type and extent of automatic controls; some have been more innovative or daring than others, but each country has moved in accordance with its own needs, preferences and particular set of circumstances.

For the most part I will say that changes in machinery plant control design, up to now, have been evolutionary rather than revolutionary. This point was made most effectively by Mr. Jan Neumann, in a paper give this past January before the Institution of Mechanical Engineers in London.(2) But while there have been national differences, there has been much in common also. For example, we all have embraced some type of digital system, and I believe we have the following concerns or constraints in common:

- o Cost
- o Reliability
- o Potential for Upgrade
- o Adaptability

With such rapid advances taking place in controls technology today, the last two items are of particular importance if we are to avoid premature obsolescence. There should be provision made in new designs to accommodate machinery plant changes, including upgrades, as well as improvements in either control system hardware or software.

FUTURE.

What of the future? Looking ahead possibly ten years or more, here are a few areas of control technology which look interesting and which I think should be pursued in research and development programs:

1. Refinement of equipment condition (health) monitoring, and extension to fault diagnosis and corrective action.

2. Robotics, possibly to eliminate dedicated actuators.

3. Artifical intelligence which can apply rules rather than steps.

Certainly the technology will continue to grow, along with an increasing demand to use the technology by the new generations of young people who will operate and maintain our ships. My distinguished colleague from the Canadian Forces, Comander Barry Taylor, has stated it so aptly: "Because of the introduction of computers into our school system, in the next ten years many of those who will be manning our Fleet will have been educated in BASIC. A failure to recognize this will result in a retrograde and perhaps the inability to recruit because of antiquated machinery control systems and an unwillingness on the part of these youngsters to give up their digital computers."

While agreeing with Commander Taylor, I must add a note of caution. The people who operate and maintain our ships today and in the future must be trained to do so without undue reliance on overly complex control systems, guided only by a digital cookbook. Navy personnel, at least, must continue to be trained and knowledgeable in all aspects of the machinery plant without regard to the degree of automation and centralized control.

CONCLUSION

David East and the members of the Symposium Committee are to be complimented for presenting a program of such high interest and potential for mutual benefit. We of the U. S. Navy expect to profit greatly, as we have in the past, from the sharing of knowledge made possible by this superbly organized forum. I hope sincerely that others will find something of equal value in the work described in our papers in these four days.

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MACHINERY CONTROL INITIATIVES - A CANADIAN PERSPECTIVE

by Cdr J.B. Taylor
LCdr D.J. Marshall
Mr. P.V. Penny
Department of National Defence(CANADA)

ABSTRACT

The evolution of a machinery control system (MCS) for warships is an interesting field of study. Generally, the approach adopted is conservative, however the end product inevitably does the job. With technology outstripping application in leaps and bounds perhaps there are better approaches to the MCS selection process. How many times have system designers generated MCS requirements that are subject to the ever present "off-the-shelf" no risk guidelines? Working within such guidelines forces one to suppress the application of current technology and condones the "what did we do before?" approach. The effect here is twofold, the current technology is left either for the next shipbuilding program or for a mid-life refit, and a fresh unbiased viewpoint is stifled by the shadow of the previous MCS. This paper will discuss an approach that could be applied to future MCS's with the view to maximizing technology benefits, minimizing risk and preventing the not so unrealistic situation of purchasing and installing an obsolescent MCS. The approach is referred to as the Continuously Advancing Development Model (CADM).

INTRODUCTION

The Canadian Navy's Shipboard Integrated Machinery Control System (SHINMACS) has been identified as the MCS for the Canadian Patrol Frigate (CPF) and is the prime candidate for the Tribal Class Update and Modernization Program (TRUMP). It has taken the Canadian Navy almost seven years to get approval to develop SHINMACS and to award a contract for an Advanced Development Model to Canadian industry. This time frame is considered to be excessive when one compares it to the lifespan of new technology. It is important to remember that prior to 1970 technology was rather slow moving hence the gap between MCS conception and installation was not as significant as it is today. What is responsible for such lengthy time frames; bureaucracy or cost or risk or a combination of all three? It is probably a combination of all three, however, by far the most significant is risk. The pricetag associated with modern warships introduces an even greater tendency to identify equipments and systems that are "off-the-shelf". This approach minimizes the risk to the program manager and the shipbuilder and is ultimately responsible for delaying the introduction of a MCS that could easily be fitted now as opposed to in the next program.

If one looks at the parallel activity of mid-life refits, and new classes of ship, there is also the tendency to retain what we had in the past because it is tried and true, or because it will keep life cycle costs down. This again evades any potential benefit that could be made in introducing new technology into service. Clearly these traditional methods work because our ships continue to pass trials and meet operational committments. The ideas and technology that were not quite off-the-shelf are not lost or abandoned however, they eventually find their way into the second generation of ship, about five years later. It is proposed that this lapse of five years can be substantially reduced with more judicious use of research and development funds. An approach that is highly promising involves channelling R&D funds to a Continuously Advancing Development Model CADM. This would provide the ideal vehicle to put new technology to sea earlier than it is currently finding its way there.

DISCUSSION

If one looks at the current process of introducing into service a system based on new technology it becomes readily apparent that it involves many steps, all of which take time to complete. The requirement must be defined; which is usually followed by the award of a contract to build an Advance Development Model (ADM). After the ADM has been evaluated a further contract is let for an Engineering Development Model (EDM) or a Service Test Model (STM), which goes on to become a pre-production prototype. This process may sound simple on the surface, but in reality a diligent effort is required to introduce new technology based systems into service. The time frames involved in this process are in the order of a decade. For those unfamiliar with the definitions of ADM, EDM, etc; these are explained in MIL-STD-280A

Continuously Advancing Development Model.

The idea of a CADM is not entirely new. It has been discussed by others, notably LCdr M.J. Langston (USN)[1], who proposed that built in obsolescence was indeed a reality that, if allowed to continue, would result in fitted systems that would not have the capability to effectively cope with the increasingly sophisticated demands of a warship.

The CADM in essence utilizes the most recent technology on the market such that in the case of a requirement for an MCS the latest conceptual thinking and developments in hardware and software would be implemented in a fully debugged ADM. Clearly, this is an attractive proposition.

In the procurement of military equipment and systems there is always a better product just slightly out of reach. This product inevitably gets left behind in a particular program because it has yet to be militarized. Militarization usually equates to risk. The unfortunate aspect of this is that the product which got left behind generally utilizes the most recent technology. This is not to say that technology for technology's sake is the ultimate goal; rather, it is stated with the view to combating obsolescence. What can be done to address the area of risk and ensure that the best systems are fitted?

Risk. Before proceeding, it is worthwhile to examine briefly what risk means with respect to identifying systems for use in warships. Risk, unfortunately, in the context of this paper can never really be properly defined. It is an intuitive feel on the part of a system designer, or more importantly, a program manager, for it is he who must be convinced that your system will not increase the risk associated with his program. To a program manager risk focuses on cost and schedule. A system may be judged to be the best in all respects; however, if the cost is excessive or the schedule is tight, the risk goes up and the likelihood of that system being fitted decreases. In the final analysis it usually comes down to fitting a system that is "off-the-shelf" or one that is about to go into production.

Militarization. Militarization of a product or system takes up a significant portion of the development time, particularly in the area of electronics. For example, a computer can take up to five years to meet the military and environmental requirements of a warship, and in that time it is well on it's way to obsolescence. If one were to use the CADM approach then militarization would cease to be a major stumbling block as it would be a concurrent event during the ongoing development. So if the risk associated with militarization is eliminated, the time frame to in-service should be reduced considerably.

CADM Approach. Assuming that there is a better approach to ensuring that desirable systems are fitted in warships and that these desirable systems are for the most part in some stage of development, they may therefore be considered, for all intents and purposes, to be "off-the-shelf".

If one was to view as a starting point the current state-of-the-art that is in service; it should be possible to develop a plan based upon continual improvement of what is already known to work. In the case of the Canadian Navy, assuming SHINMACS was fitted in the current fleet, this would involve setting up a laboratory with the most recent version of SHINMACS. As new ideas, languages and hardware became available the most promising would be incorporated into SHINMACS to determine their feasibility for application in a warship environment. When a new ship program is announced, or a mid-life refit is approaching, a decision would be made to freeze the SHINMACS laboratory development such that the design to date would be taken to production. Clearly the risk of this "off-the-shelf" system not meeting the applicable performance or schedule requirements would be minimized. In addition, estimates of shipset costs would be much more accurate; this is attractive to a program manager who is continuously wrestling with estimates that can be in error by as much as fifty percent.

Ignoring, for the moment, the detailed mechanics of implementing a CADM, let us examine the implications of such an approach. Governments are continuously admonished by industry for their lacklustre approach to R&D. A CADM is an ideal vehicle to involve industry in a high technology venture that would have foreign sales potential and the distinct possibility of marketable spinoffs. How should a CADM be funded? How would a CADM be awarded? For what length of time would the contract be awarded prior to re-tendering? Possibly incentives in the form of royalties could be offered to ensure that a company is maintaining a certain level of effort. All of these questions and, no doubt, many more would have to be considered and resolved if the CADM approach is to succeed.

MACHINERY CONTROL SYSTEM FOR THE CPF

The evolution of the MCS for the Canadian Patrol Frigate is an interesting case in light of the direction that it be "off-the-shelf". The specification was written in 1977 and was based to a large extent on what was fitted in the DDH 280 and the results of a digital system feasibility study. The specification could not be definitive but had to guess at what would be "off-the-shelf" for the first CPF which is scheduled for delivery in 1988.

In moving toward identification of a MCS that could be considered "off-the-shelf" by the time the CPF was to go to contract, two minor R&D projects were initiated. The first was to build a simulation of the DDH 280 machinery plant that would be used for testing new concepts. The work of Gorrell[2] was examined in detail, eventually resulting in a contract to build a man-machine interface demonstrator that would be used to show that it was possible to use visual display units as an effective means to interrogate and control the machinery plant of a warship. The demonstrator, known as the Standard Machinery Control Console (SMCC), was delivered to DND in December 1983. In this step a great stride has been made in the use of technology to make the operator a more effective decision maker. As shown in Fig. 1, the operator no longer has to memorize systems diagrams as the MCS will display them to the operator on request. The introduction of this technology must be done in conjunction with modifications to the training system such that the trainee can more effectivly utilize his training time to learn systems engineering as opposed to memorizing system diagrams.

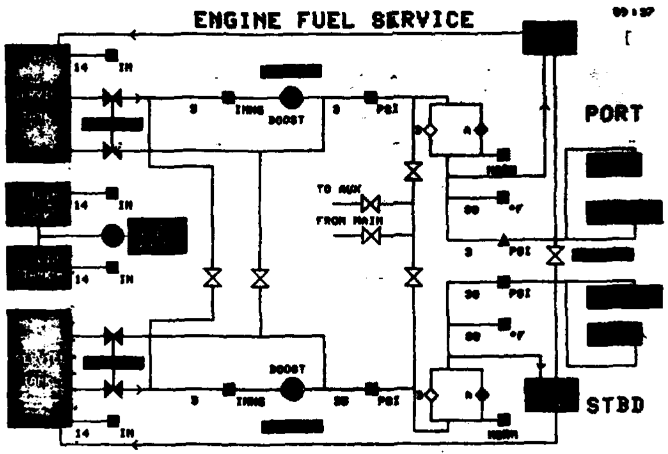

Figure 1. Typical System Graphic

Since the delivery of the SMCC, a great deal of effort has gone into evaluating the concept. This has been described in detail by, Marshall[3], and Turner et al[4]. In parallel with this work, a further contract was let to a Canadian company for an Advanced Development Model (ADM) of the Canadian Forces SHipboard INtegrated Machinery Control System (SHINMACS). This development encompasses the whole DDH 280 machinery plant and demonstrates not only the man-machine interface, but also the concept of a distributed architecture utilizing a data highway. The display technology in SHINMACS also permits the inclusion of an extensive plant diagnostics program as described by MacGillivray et al[6]. The ADM is scheduled for delivery in June 1985.

Although the above may initially appear to be rather straight forward and simple, such was not the case. The ever present "off-the-shelf" criterion versus risk was a major hurdle that SHINMACS had to address at every turn. Considering that SHINMACS was conceived in 1977, and that it has now been identified for the CPF[5], the impact of delays noted by Langston[1] have certainly been verified as the SHINMACS ADM is being built in militarized hardware that is virtually obsolescent.

If the CADM had been in place in 1977, then in 1983 when the CPF Program contract was signed, the CADM for a MCS would have been frozen in design; the technical documents would have been issued to the contractor to build a production system; the Program Manager would have a realistic cost estimate of the system; and all of the arguments of "off-the-shelf" risk would no longer be valid. In the meantime, the CADM would continue in development such that for the next ship program, or modernization, the MCS would inevitably end up being the son of that in the CPF. Inherent within this last statement is the infrastructure for sensible life cycle materiel management.

Technology and CADM

How many times has one heard statements such as: "Can we use fibreoptics?"; "Has it been designed for EMP and TREE?"; "Will it use VLSI?"; "Will any of the spinoffs of the VHISIC program be incorporated?". Generally the answers are non-committal or an outright "No". In this day of sophisticated maritime scenarios these answers are not good enough. A CADM could be used to incorporate selected technologies thus ensuring that knowledgeable answers would be available when the program manager of the next ship design is ready for an "off-the-shelf" design of a machinery control system.

Artificial intelligence is making great inroads in many fields. Why should it be excluded from machinery control systems? The answer is, it should not. Artificial intelligence could be used to talk to a machinery control operator when, for example, an alarm goes off and the operator exclaims "What was that?". The computer would answer the question and possibly discuss courses of action with the operator. It is important to realize that man is not being eliminated in favour of artificial intelligence rather he is in the loop in an interactive role. Clearly, just as graphics were used to aid the operator in learning his systems, artificial intelligence could be used to make the operator a better systems manager by relieving him of some of the mundane memory work currrently required in the management of machinery and its associated systems. As in the previous case a CADM could be utilized to define and develop the role of artificial intelligence in machinery control.

In looking at larger scale integration of shipboard systems, it is envisaged that it will be possible to integrate the ship's navigation system with the ship's machinery control system. This will not be an autopilot as we know it today, rather it will be in the form of a totally integrated system such that the electronic navigator will actually command the machinery control system to make the ship respond to the directions provided by the ship's navigator. Thus the ship's position could continually be amended to ensure that she remains on track and meets the scheduled time of arrival. A CADM is an ideal development tool with which to make exhaustive investigations in this and other areas of larger scale integration.

It is clear from this discussion that there is a requirement to shorten the time from conception to in-service. If one considers the current view of government to contract-out work in order to sustain the industrial base; then clearly R&D monies should be used more effectively to ensure that the Navy receives systems that incorporate the benefits of the technological improvements. The CADM is a vehicle to do this type of work in that it provides a flexible vehicle to do continuous development in a particular field of endeavour and shortens the development timeframes. In meeting the requirements of the ship program manager, the CADM will provide an "off-the-shelf" system that would be relatively free of risk. The CADM would also sharpen the industrial competition by the process that all CADM's would be awarded on a tender basis to companys resident within the country.

CONCLUSIONS

The time lag, from conception to in-service, has always been a problem, and is becoming more of a problem given that advances in technology are occuring at a faster rate than in the past. In order to shorten the development time from conception to in-service, the CADM is proposed as a viable alternative.

CADM work should be funded by government to industry and various academic institutions. CADM's should be awarded on a tender basis for a block period of time with the post initial funding being provided as per the normal government budgetary estimates. The addition of new concepts to the CADM could be identified in a coherent manner by either government or civilian industry, and implemented on mutual agreement. The adoption of the various government standards in the areas of interfaces and software should ensure that a monopoly isn't created in any particular field.

The CADM provides the best benefit to the new ship program manager in that he is assured of systems that are "off-tne-shelf", low in risk, and reasonably well defined in terms of cost. The winner, of course, is the Navy in that it has new technologies introduced into service at a much earlier point in the normal 25 year service period of a ship.

NOTE: The opinions expressed herein are those of the authors, they are not to be construed as those of the Department of National Defence.

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SHIP AUTOMATION, A DUTCH VIEW ON PRACTICE AND PROGRESS

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ABSTRACT

1. The fundamental purpose of ship automation activities is defined by the strategy of the shipowner and hence varies according to his specific requirements. The main distinction to be made in this paper, is between the commercial and military operator. Their respective aims set the scene not only for future developments in the field, but also dictate to a large extent the direction which future research is to take. The paper endeavours to clarify some of the policies which guide conceptual thinking on the subject of ship automation in relation to the operator's aims.

INTRODUCTION

2. The question whether a ship or its systems should be automated is now purely academic. The relevant questions to be asked, regard the nature and the extent of automation requirements for present- day ships.
Even more dominant is the matter of policy which will eventually dictate the course and shape of future automation efforts.
Dutch shipping, naval and commercial, does not constitute an isolated entity. Technical advances and legal constraints have a boundary crossing relevance. Therefore a strong relation exists between developments at home and those abroad. Furthermore, ship systems vary enormously depending on the strategic positioning, which forms the basis of their underlying design objectives. However, it has frequently been demonstrated in the past, that naval and merchant operators may come to the same conclusions and the same solutions, albeit for entirely different reasons.
Thoughts about future trends in ship automation in the Dutch shipping and shipbuilding industry, can only be meaningful if they are supported by an examination of the present position of ship automation and of the vastly differing objectives and constraints, which are relevant to specific operations.

WHO CALLS THE TUNE?

3. The shipowner, be he merchant or military, will generally insist that his requirements are the prime mover for development of ship control systems. He will complain of the non-availability of sufficiently advanced systems at the time he wants them (1). And when they are available, reliable and maintenance free, they are often considered to be too expensive (2). Their complaints are echoed by operators in varying permutations and combinations; the main theme remains that the controls industry has been dragging its heels.
On the other hand, industry concerned with automation, will argue that technically speaking, nothing is beyond their capacity. They will point out with subtlety that space travel -both manned and unmanned- can only serve to certify their ability to handle problems to a degree of complexity which is fully capable to take on any of the technical challenges offered by maritime requirements.

As it happens, it is precisely the specific nature of these requirements which makes the gap between supply and demand so difficult to bridge. The next section of this paper will therefore be devoted to a closer look at the characteristic needs of the maritime operator.

4. DIFFERENCES AND SIMILARITIES

4.1 Navies & merchant operators share a common ally ànd ennemy: the sea. The sea is generally regarded as a hostile environment in a broad sense. From its presence stems a common basis for requirements for marine automation:

a. High availability through optimum reliability and maintainability.
b. Economy of weight and space.
c. A satisfactory installation layout, which provides for ease of operation and accessibility.
d. Fault tolerant character.
e. Flexibility in many senses.
f. Resistance to physical marine conditions such as flexing, vibration, humidity, temperature and salt corrosion.

4.2 Where naval and merchant system requirements differ, is exemplified by the following distinction:

a. Efficiency. The commercial operator measures effectiveness as a result to effort ratio (i.e. cost effectiveness) with the aim of profit maximisation. Investment is judged on return.
b. Efficacy. The naval operator aims to maximise his (operational) service in a cost conscious way. However, since governments tend to judge investments principally on yearly budgets and cash limits, payback time is hardly relevant in a political sense. Through life cost therefore, regrettably comes second.

4.3 Another difference of course, between naval and commercial operators arises from the type of operation. Warships and their systems are designed to sustain damage of all kinds, inflicted on purpose by an ennemy, with a minimum loss of operational capability. This leads to extensive compartimentalisation and duplication of all systems in the case of naval design (3). The merchant ship on the other hand, will be designed to sustain only a certain amount of damage resulting from peacetime accidents (collision, fire, flooding, as opposed to rocket blast and bomb explosion).

4.4 A third difference is the manpower policy as currently seen by both types of operator. The merchant fleet aims for minimum manning, possibly down to zero, on a basis of through cost reduction. The navy may minimise manpower for reasons of cost reduction, but will not as yet go to the extreme of crewless ships, for reasons of command and direction, and because of specific damage control and upkeep requirements.

5. REQUIREMENTS BREED AIMS

From paragraph 4 it is possible to draw a rough outline of the aims for the different types of operators.

5.1 Merchant

a. In the medium term the aim will be the phased replacement of manpower by automated systems. The rate at which this is to take place will depend on many factors, the overriding one being cost effectiveness.
b. In the long term, merchant shipping aims for the unmanned ship, subject to demonstrated economic justification.

5.2 Naval

a. The medium term aim in the naval field stems from the requirements which are based on the "one man control"-philosophy for the platform. This means that one man is permanently present in a machinery control room, while another is available for rounds and generally for minor trouble shooting activities. This results in a minimum ship's complement requirement for operational and maintenance tasks. Where up to now the weapons engineer and the mechanical engineer went their own separate way in systems and equipment, standardisation in hardware will be actively pursued from now on.

b. In the long term a progressing standardisation can be expected. Due to different requirements of operational command and control on one hand, and of ship platform control on the other, total functional and technical integration is thought to be Utopia in the context of warship design. However a useful level of functional and technical integration will be the aim to such an extent, that price, performance, reliability and responsibility are attuned sensibly.

6. STUMBLING BLOCKS AND ICY PATCHES

6.1 In their efforts to achieve the goals laid down in para 5, shipowners come across a number of problems that remain to be solved:

6.2 The introduction of control gear increases quantity of equipment. An increased quantity of equipment generally means:

a. more component failures and;

b. a higher on board maintenance load.

These problems require technical solutions:

a. Availability must be improved by enhancing component and system reliability.

b. The on board maintenance load must be reduced by increasing reliability (4), and by shifting the maintenance load from ship to shore (5). The latter can be achieved by changing to a suitable maintenance policy such as Upkeep by Exchange.

6.3 Manpower requirements pose a number of problems of their own:

a. With an increasing complexity of automated systems, it is essential that the system structure remains transparent for the run of the mill user/maintainer on board. An increased demand will be put on crew ability to handle systems rather than equipments.

b. The progressive integration of on board systems across the traditional boundaries between disciplines, increases the need for further cross-training of crew.

c. Mechanical failures are usually easy to diagnose and difficult to repair. For electronic failures the reverse tends to be true. The large scale introduction of electronic systems will increasingly tax the operator's ability to understand and diagnose the behaviour of his equipment.

Then there must be a limit to what can be expected of one man. The sea has always attracted the practical rather than the academic man. It will therefore be increasingly difficult to find the right sort of man to crew the future ship. This fact in itself will accelerate the automation process, and will -paradoxically- turn the zero crew ship into a more and more sensible proposition. It looks as though the navy, in not aiming for zero manning, has a lasting problem on its hand.

7. BOTTOM UP OR TOP DOWN

7.1 History has shown the beginning of ship automation as a bottom up process. This is usually the way spontaneous developments evolve. The reasons why are clear.

a. The need for automation made itself felt most in discrete process functions which were characterised by tedium and by a requirement for continued alertness and in some cases accuracy. Boiler feed controls and electrical voltage and frequency controllers are excellent examples.

b. Thinking in terms of functional systems is something that has evolved over the years. Propulsion designs and engine room designs traditionally consisted of a rather loosely matched conglomerate of equipments and appliances.

If any systems approach was applied at all, it related to physical systems in most cases. The understanding of functional systems provided a critical breakthrough.

c. Control technology has evolved conceptually from analogue to digital systems, and technically from hydro-mechanical systems to electronic systems.

Pneumatics, mechanics and hydraulics in comparison with electronic systems, are capital intensive, power demanding, unreliable if complex, maintenance intensive and slow acting. These characteristics prohibit large scale integration in the same way they caused Babbage's Analytical Engine to founder (6).

7.2 A bottom up approach is nearly always a good start for a beginner. It requires a minimum of abstraction at a moment when thinking on a level of any real significance. Most learner curves begin this way. This approach is also in keeping with the desire to keep things cheap and simple in the case of limited application with limited goals. In the case of ship automation, one is to think here for instance of automation of an evaporator in isolation from other machinery systems, or of a proportional boiler feed controller. However, if the aim is to optimise not just one piece of equipment, but a whole system, the bottom up approach is no longer suitable as a result of mainly human limitations.

a. The number of controls to be handled and the information to be processed become too overwhelming for human capacity.

b. Optimisation is a funny and above all complex game. It requires different sets of rules for different circumstances. Cost functions loose their significance and criteria are no longer valid if operational or commercial conditions change. For instance the trade off between fuel economy and turn around time of a cargo ship may depend on the nature of the goods it carries. It is not realistic to expect the human operator to be able to avoid suboptimal operation in changing circumstances.

c. For complicated systems the task of specification of system requirements becomes near impossible where bottom up methods are employed. Conversely, such a specification is extremely difficult to translate into a design which is safe, logic, cost effective and at the same time complies with the expectations of the prospective operator.

7.3 The arguments in the two foregoing paragraphs point firmly in the direction of a top down approach as the standard for things to come. Clearly such an approach requires a deep conceptual understanding of the ship as a system. However, no less important is the neccessity to realise that restraint is required, when deciding which functions and relationships ought to be considered for automation and which not. The choices to be made, require value judgement. The relative importance of parameters is not always obvious, as every chief engineer knows when dividing his priorities between his propellor revs and the captain's shower. However, the whole system must be fully considered in the first instance before restrictive decisions are made.

8. THE NEXT STEP

8.1 Medium term efforts will be governed by a number of developments, some more or less autonomous, others heavily depending on strategic reasoning, either military or commercial. The aims as suggested in paragraph 5, are obviously of prime importance. The roads along which these aims are to be reached, depend heavily on industrial development. At any rate a top down philosophy will take preference. The speed at which all this takes place is likely to be a function of market developments and legal endorsement by governments and classification societies (7).

8.2 In the naval field a top down philosophy is accepted. The process of manning reduction in warships has gone as fas as practical; particularly bearing in mind the constant need for routine maintenance and the occasional need for damage control and energency repair (8).
In automatic control systems the sensors and transducers appear to be the weak link. It is imperative that the utmost attention is given to the development of sensors and transducers in terms of higher reliability and accuracy, without making them prohibitively expensive. The human-being on the other hand often is the weakest link in the system. Research into human failure has to be carried out seriously. Further development of the man/machine interface for safer and error-free operation needs to be undertaken.

8.3 From a merchant point of view the previously stated aim dominates the scene, i.e. phased replacement of manpower by automated systems on a basis of cost effectiveness. The way in which this manpower reduction will take place can be deducted by answering the question who will be the last man on board. He is almost certainly not to be found in the engine room or the radio cabin, but on the bridge. In other words, the bridge increasingly becomes the operational heart of the ship, where all tasks are being planned and executed. This encompasses operational planning, navigation and communication, as well as control and monitoring of the system ship and its constituent subsystems. This raises questions not only regarding the range of skills and knowlegde that can be encompassed by one man, but also about the workload he may be subjected to, without impairing his judgement in critical circumstances as a result of overburdening.

9. RESEARCH: MORE THAN DEDUCTION

9.1 In order to maintain the distinction made in paragraph 8.1 between autonomous developments and strategically supported research we will briefly look at what is currently being done in the world and how the Netherlands research community responds to the challenges offered by a changing environment.

9.2 The number of autonomous developments aimed at replacement of the human factor on board increases by the day. Examples are:

- robotic tank cleaners (9),
- adaptive autopilots (10),
- collision avoidance and routing systems (11),
- digital engine control (12, 13),
- ship-shore and ship-ship data links (14) and last but not least
- machinery voice control (What happens if His Master's Voice has a cold?) (15).

All these developments are building bricks, which need to be integrated into a larger control structure. Great efforts are being made to achieve this integration. References (16), (17), (18) and (19) indicate a high level of activity, supporting the view that a top down approach is unavoidable.

9.3 Research programmes in the Netherlands, jointly supported by shipowners, shipbuilders and government concentrate in the main on issues concerning the analysis of human failure, the centralised bridge concept, limits to operational stress, cross training of seamen and engineers, and development of a conceptual method for the functional analysis of ships.
All these programmes address themselves to ship design itself. But of course it is inconceivable, that a hi-tech ship will come into being without a corresponding hi-tech shore organisation to match it. Ships need to be received alongside, guided, loaded and unloaded, communicated with, fuelled. To attempt to solve the problem ship, whithout tackling these aspects, would be a recipe for inglorious failure. The importance of this fact is now widely accepted. Research programmes covering a fundamental systems approach to the ship-shore relationship are gathering pace. This summing up is by no means exhaustive, but it clearly reflects the way thinking has evolved in recent years in the Dutch maritime community.

9.4 In terms of research, this leaves one aspect which, with a few exceptions, remains largely underexposed: reliability. The concept allows itself to be handled in a very practical manner where electronic networks and systems are concerned. But that is less than half the story for the automated ship. Paragraph 8.2 already mentioned the traumatic question of sensors. Even less hopeful is the situation when it comes to assessing and designing for reliability of the system which is to be automated i.e. the hull including all mechanical and hydraulic systems and structures. Only nuclear engineers and aircraft manufactures have so far proven to possess a working knowledge of reliability in this field. The naval architect and the marine engineer alike, are groping in the dark when it comes to application of vague statistical concepts. That university training on the subject is inadequate, is hardly surprising. Research has only just started. Too late; let us hope is won't be too little.

10. A LONG SHOT

10.1 The long term aims formulated in section 5 of this paper are different for naval and commercial applications. The outward difference lies in the disappearance of crew in the merchant case, while the warship will continue to be manned. The underlying cause for this discrepancy is the overriding requirement for a merchant ship to make money, whereas the naval operator has the problem of having to weight cost in relation to effectiveness in action.

10.2 For these reasons, the commercial man only has to follow his instincts. The price of manpower is going up whilst the cost of automation comes down. Does it mean that the unmanned ship will be a commonplace reality in the future?. That it will become a reality, is something no one doubts, since the announcement of an experimental zero-crew crossing from Tokyo to Seattle, to be effected in November 1985 (20). Whether it becomes a commonplace occurrance is a different matter altogether.
More than one operational scenario is possible. Convoys of unmanned ships might be shepherded along by one manned ship. Alternatively ships might be directed via sattelite links from a number of shore based mission control centres or from a network of stationary guidance vessels. Many questions of safety, however, remain to be dealt with. For the seamen (who will always exist) one Flying Dutchman is quite enough. Also insurance premiums will not remain unaffected, and above all, who can envisage the French and British authorities rejoicing at the sight of a steady stream of Ultra Large Crude Carriers bound for Rotterdam through the Dover Straits and not a soul on board?

Then there remains the matter of good faith. What to think about a company breaking into someone else's data links, thus diverting their competitor's ship, while faking the ship status reports so the owner doesn't notice. Or worse, a hostile nation which by surprise renders enemy harbours inaccessible by causing ships to collide or run aground in confined waters by remote control? All this may serve to demonstrate the complexities of large scale unmanned ship operation. Nevertheless the required technology is available now (21). That unmanned shipping will exist in some form or another can be predicted with confidence.

10.3 As pointed out in the previous paragraphs the expectation is that warships, contrary to merchant ships, will not be unmanned in the future (this does not necessarily imply a permanently manned machinery control room). This leaves one hitherto non-existent problem to be sorted out: "How to manage a convoy consisting of unmanned merchant ships and manned warships, in wartime conditions?

CONCLUSIONS

11. From the foregoing review, a number of conclusions can be drawn regarding future automation trends in Dutch shipping and shipbuilding:

a. Whilst the unmanned warship has no place in current thinking, the zero crew merchant vessel must be considered to be a realistic goal.

b. System and component reliability remain key issues in deciding the feasibility of unmanned shipping.

c. Progressive automation puts such severe demands on the remaining crew, that this fact in itself constitutes a major incentive for eliminating the need for ship's staff altogether.

d. A top down approach is the only way in which a unified control concept can be developed successfully. In this process, the development of the bridge as an integrated operational centre will be an essential, but passing stage.

THE END IS NOT NIGH

12. The reader may be left with the impression that with a general outline of the course to follow and the target to achieve, ship automation will be finished (=completed) in say 10 years time. Nothing left to be done! To think so would be to fool ourselves. What lies beyond the horizon, which this paper has tried to outline, is difficult to predict. A few elements, however, are already visible. One of these is technology. Light processing and optical data transmission and storage are a sign of things to come. Their impact on the direction of automation will be enormous, not to mention the consequences of technologies still unknown to us. Another source of change is the advent of artificial intelligence. Again the shape of the future is difficult to perceive, but it requires only little imagination to see an extensive role for expert systems in a problem solving environment like ship operation. It should be realised, however, that these developments may turn out to be insignificant when compared with the importance of developments in the relations between states and powers. One crystal ball will hardly be enough. On the subject of optics and artificial intelligence however, the 1987 Ship Control Systems Symposium may come up with some more clues.

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DIGITAL CONTROL AND SURVEILLANCE SYSTEM FOR THE M -CLASS FRIGATE OF THE ROYAL NETHERLANDS NAVY

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ABSTRACT

The new class of ocean going Multipurpose "M" frigates for the Royal Netherlands Navy is entering the procurment phase.
The Control and Surveillance system for this new class of ships will be based on the system designed for the Walrus-class submarine.
The complement of the M-class frigate, in engineers, will be significantly reduced compaired with the previous class of "S" frigates (Kortenaer-class).
The complement of the "S" frigates has been determined as the minimum to fulfill the tasks of maintenance and watchkeeping.
The maintenance load on the M-class frigate is expected to be at least as high and so the number of watchkeepers must be reduced.
In fact, this requires a Control and Surveillance system that allows one operator to monitor and control the entire platform.
In this paper the influence of the "one" man control philosophy on the system layout, the integration of all platform systems into a integrated and cost effective Control and Surveillance System, and some of the problems encountered during the system definition will be discussed.

INTRODUCTION

When the design criteria of the M-class frigate were formulated, it became clear that the number of mechanical and electrical engineers would suffer a major reduction compared with the S-class frigates (Kortenaer-class).
Some authors like to compare different classes of ships in tables which show numbers of engineers versus installed power or tonnage.
This will not properly reveal the seriousness of the trend we are facing.
The M-class frigate is a good example.
This ship will have a two diesel/two gas turbine CODOG propulsion plant with two shafts and controllable pitch propellors.
She will be a smaller (in tonnage) ship than the S-class frigate and will have less installed power.
On the other hand the "platform" installation of the M-class frigate will be as complex as the installation in the S-class frigates.
Table 1 shows the number of engineers employed for installations which have comparable degree of complexity.
The figures of engineers on the Tromp-class frigates have been given the index 100.

Table 1	Commissioned	index of engineers per 1 MW installed power	index of engineers per 1000 ton displacement	index of engineers on board
Tromp-class	1975	100	100	100
Kortenaer-class	1978	87	101	87
M-class	1988	71	83	65

Within 15 years the number of technical "platform" personnel, on ships with comparable complexity, has been cut by 35%.

The task of the engineers can be divided in two parts:

- watchkeeping
- maintenance

However the crew is organized, these two main functions have to be fullfilled.
With simular complexity in the installation and an equivalant maintenance load expected, it was considered undesirable to reduce the number of "maintainers".
So the only means to cope with the new reduction of personnel is a reduction of the number of watchkeepers.
Reducing the number of watchkeepers without sacrificing the highly desirable operational flexibility calls for a sophisticated Control and Surveillance System.

At the start of 1984 the decision was made to investigate if it would be financially possible to use the "ship type independent" part of the Walrus-class submarine Control and Surveillance System together with its control philosophy as a basis for the Control and Surveillance System on the M class frigate.

PROGRESS WITH THE WALRUS-CLASS CONTROL AND SURVEILLANCE SYSTEM

The Control and Surveillance System for the Walrus-class submarine which was introduced at the 6th Ship Control System Symposium in Ottawa (1), is still in full development and reaching the stage of protoytpe testing of Local Processing Units and Dedicated Control Systems.
Although it will take at least another year before the complete system can be tested in a simulated environment, a stage has been reached where the system layout, functions (etc) are defined.
Some of the problems encountered during the development are worthwhile mentioning:
A major effort had to be made to obtain a good set of detailed installation descriptions in order to enable the programmer to write software for Dedicated Control Systems and to assign functions to Dedicated Control panels and Emergency Control panels.
In an early phase and after convincing all participating that these detailed descriptions were essential for a successful design, it became clear that a systematic approach had to be made.
This resulted in the application of a fixed format for these descriptions which can be used for all the ships systems.
In all it took about three years to get all the systems properly described.
Making these system descriptions was especially difficult because of the specialized nature of the ship, a submarine, with all its safety features vital systems and operational modes (like snorting).
Choosing a submarine as the first installation to introduce digital programmable computer systems in an integrated Control and Surveillance System of this magnitude is rather like jumping in at the deep end.

Another problem is to avoid contradictions within the system.
Once a choice has been made about control philosophies one must stick to it although very soon an occasion will present itself where it seems to be better to do it another way.

Some examples of these philosophies are:

- Use of independent sensors for the functions
  control
  safety
  surveillance
- Control can be only exercised from one position a time
- System Independent functions must have their own independent power supply, sensors and controls.
- Change over of control modes must be simular for all the control systems.

Experience suggests that it will take quite an effort to always satisfy these requirements, and to guard them against intrusion during the system development.

Essential parts of the system are operational and ergonomical optimally designed system mimics, which are presented on colour VDU's. Limiting factors in the design of the mimics are the VDU, the colour processor and its picture editor.
In order to have a starting point, certain decisions on hardware must be made at an early stage.
These decisions will impose constraints on the system.
Later newly developed hardware will be available which could solve problems encountered during the design of the mimics.
Then it is very convenient if the design allows for the application of more advanced hardware.
For example, for the Walrus-system a change was made from Nordon PDP 11-34 to Nordon PDP 11-44 computers, and a more advanced picture processor solved a lot of the ergonomic and software problems encountered during the design of the mimics.
Certainly it is advantageous to be able to postpone the final hardware decision until a time as close as possible to the moment of system realization.

THE M-CLASS FRIGATE CONTROL AND SURVEILLANCE SYSTEM

In the end of 1983 the decision was made by the Dutch government to start the M-class (multipurpose)frigate programme, in order to ensure employment in the shipbuilding industry.
Evaluation of the staff requirements, which called for a drastic reduction of engineers, made it clear that a Control and Surveillance System of the the magnitude of the Walrus-class submarine system would be necessary to ensure a responsible, safe and flexible operation of the installations.
The decision was made to use the "Ship-type independent" part of the Walrus system and to develop the typical M-frigate applications.
This decision is based on faith in the Walrus-class system design which is in its final stage of development and the prospect of large savings on development costs.
The principle diagram of the Control and Surveillance System can be seen in figure 1.

figure 1. Principle diagram Control and Surveillance system.

The aims of the design

The first aim is to realize the system within a budget which is comparable with the budget spent on Control and Surveillance in the S-class frigates.
The second aim is to integrate all "platform" installations in the Control and Surveillance System using the standarized systems hardware, from the Gas Turbines to the Automatic Self adapting Steering and Roll reducing controls.
The third and most important aim is to design a system which will enable the (reduced) crew to efficiently and safely monitor and control the platform.

The realisation

Between the first and the third aim is a possible conflict which can only be tackled when the total system has been defined, because only then it will be possible to check whether the budget has been met.
This paper reflects the RNLN view about the way the M-frigate Control and Surveillance System should be (honouring the first aim).
Time alone will tell if the all aims will be met.
There are some bright spots in the dark sky.

- Digital systems are not cheap but standardizing will reduce the costs.
- The use of serial datalines will reduce the amount of cabling which was a major item in the Kortenaer-class budget.
- Installing the Dedicated Control Units as close as possible to the machinery will also reduce cabling.
- Using several alarm limits (software wise) from one analog sensor avoids the cost of installing several digital sensors.
- VDU's will reduce the amount of (highly expensive) dedicated control panels in the MCR.

In the field of sensors, savings are also possible.

- All electrical sensors can be read out on their Dedicated Control Units or their local Processing Units.
- Local sensors will only be installed if they are absolutely necessary to operate the installation safely when the Integrated Control and Surveillance System has broken down (which is highly improbable).
- The checking of electrical sensors will in principle be done by portable instruments using plug-in connections.

The amount of sensors really needed to control an installation and the amount of remote controls necessary to control the "platform" in the first 5-10 minutes after an emergency with the reduced watchkeeping team, are fixed in a detailled evaluation of each system.

The second aim, standardization, is a troublesome road.
For one thing it means, for a major part of the control systems at least, going digital, using standard hardware and fitting into the system philosophy.
Although digital controls are fully accepted by the RNlN and are being installed in the new Walrus-class submarines, this does not mean that the battle is won.
A lot of talking and convincing must still be done.
It is difficult to calculate the effect of a decision on the total system.
Certainly, it can be cheaper to use old fashioned "proven" analog controls, but is it still cheaper if interfaces and cabling needed to get the information to the proper places (MCR) are included, as well as all the special spare parts a ship would have to carry, not mentioning the specialized training of the maintenance crew??
Standardization will mean:

One type of microprocessor for local Processing Units and Dedicated Control Units;
Standardized Sensor Interfaces;
Standardized main computers (including weapon and logistic computers).

The third aim addresses the degree of automation.
The watchkeeping team will be reduced to such an extent that during normal "routine" sailing only two engineers will be on watch in the MCR.
Since one of them is not restricted to the MCR (rounds, checks, coffee, etc) the Control and Surveillance installations must be so extensive that one man can effectively and safely control the ship and can cope with emergencies.
More than ever the MCR will be the place of control and supervision since all information will be available there, real time and organized in the best ergonomic way.

Hardware

The M-frigate project has very tight budgetary constraints.
The main area's for potential savings will be:

Development
Installation
Spare parts
Training

A lot of effort is spent on the search for cheaper hardware without sacrificing performance.
Compared with five years ago, it is possible to get improved performance for the same price.

- The two main computers will be rugidised civil VAC-750's.
- These computers, able to withstand all the ships environmental conditions, give a substantial saving compaired with the Milspec Nordon PDP-11/44 main computers on board of the Walrus-class submarines and will be a "stronger" main computer, a development which was not unwelcome because of the wish to also integrate NBCD-features in the system.
- For the microprocessor used in the local Processing Units and the Dedicated Control Systems (LSI-11 on the Walrus-class submarine) a stronger microprosessor will be installed, also within the "more performance for the same investment" line.

VDU's, colour processors, disks an other peripherals will mostly be based on the choices made for the "Walrus hardware", but also including the possibility of adapting the peripherals in a later stage in line with new technical developments.
The printers will be of a fully graphic type which will create the opportunity to get hard copies of system states, NBCD compilations and trend graphs.
Sensors and interfaces will be standardized.
The sensors will be chosen depending the demands of the typical application, but sensor outputs will be standardized which will limit the number of different sensor interfaces.

Features of the system

The Control and Surveillance system of the M-frigate will use the ship-type independent part of the Walrus Control and Surveillance System. There is a lot more room available on board a surface ship and it will be a second generation system so there are differences.
On the Walrus class submarine the man-machine interface consists of two control positions, each with a colour VDU and a plasma alfanumeric screen (alarm screen) fig 2.

figure 2. Walrus class control positions.

There are also a large number of dedicated panels, for control assignment, system surveillance, dedicated controls and emergency controls.
Some of these panels are typical for a submarine where redundancy and safety are required.
On the M frigate the aim will be reduce the amount of panels drasticaly.
As far as can be forseen, in this phase of the design, there will be a propulsion control panel including a push button telegraph and some special purpose function keys.
All the other control functions will take place through the integrated Control and Surveillance System using VDU's.
The MCR will have three control positions with three colour VDU's each, one for alfanumeric alarm information, the other two for surveillance and control.
Excluding a minimum of special panels, the control positions will be identical and each task can be reassigned between them.

For the overall control there are two management positions with one colour VDU each, which can display all the information present in the system.
From these positions, equipped with extensive communication facilities it will be possible to manage the platform actions, including NBCD.
The system has two redundant main computers one located in the ship near the MCR, the other in the forward part. The system load is shared between the computers.
All information is available in both main computers and they are hot stand by for the tasks allocated to the other computer.
This feature and the possibility to allocate random tasks to random control positions gives the opportunity to create a control position in the forward section of the ship which will be used as a stand by MCR and which can take full control should the environment in the MCR become uninhabitable (regardless the condition of the aft main computer!).
To be able to profit from this redundant configuration all cabling will be concentrated in those parts of the ship that have a low vulnerability.

Propulsion Control

The CODOG (SW 280/RR Spey) installation of the M-frigate is controlled by the Propulsion Control System. This system uses the standardized Control and Surveillance hardware and is fully integrated in the platform Control and Surveillance system.
This system has two identical parts
Each part controls one shaft and consists of:

- Propulsion manager;
- Diesel engine control system;
- Gas turbine control system.

The propulsion managers are linked with a data link for status information exchange, otherwise they are independent.
The propulsion manager incorporates the push button telegraph and controls its diesel engine and gas turbine control systems, clutches and controllable pitch propellor.
The diesel control system and the gas turbine control system receive "set points" from the propulsion manager.
These set points are checked against limits and the engine will be controlled in such a way that undesired and "unhealthy" situations are avoided.
Pre start interlocks are also checked and fully controlled starting and stopping sequences are included.

There are several levels of control which allow for a gradual degradation of the system in case of a breakdown.
Remote control with the push button telegraph (a dedicated control panel of the propulsion manager) is possible on the bridge, in the OPS room and in the MCR.
Further remote control functions, like engine configuration changes and starting/stopping of engines can be done from the propulsion control panel in the MCR.
All these remote control functions can also be done locally on the propulsion manager itself (which will be located near the main gearbox).
Starting/stopping and set point control of an engine can be done from remote on the Control and Surveillance Systems VDU's by giving orders to the engine control systems.
Locally this is also possible on the engine control systems themselves (which will be located near each engine).
Direct remote control of the engine throttles will be possible with special function keys of the Control and Surveillance System.
Of course local control of the throttles will also be possible.
To ensure a safe propulsion control under all circumstances all local control positions are equipped with the necessary communication equipment.

Electric energy generating and distributing system

The electric energy generating and distributing system has four diesel generator sets with four identical control systems.
Each control system controls a diesel generator and a part of a switchboard.
Automatic starting/stopping, paralleling, and load sharing are the main features.
A selective switching off of user groups in case of a overload situation will also be incorporated.

Rudder Roll Stabilisation

The M frigate will use its rudders for roll stabilisation.
The roll stabilisation and the autopilot steering functions will be controlled by two redundant control systems (also standardized and fully integrated in the platform Control and Surveillance System).
The system is self adaptive to the outside conditions and offers several control modes.
Dedicated remote control panels are located on the bridge and in the OPS room.
A local control panel is situated on the control systems cabinet located aft in the ship, near to the rudders, which also functions as emergency steering position.

Damage Control

The conventional Damage Control board has many disadvantages, lacks flexibility and is restricted in its use as an overview of the NBCD situation, while the huge amount of sensors and cabling makes it expensive.
So an investigation is being made to see if it would be possible to integrate NBCD in the Control and Surveillance system.
The price tag should not exceed the price tag of a conventional system.
The integration would mean that all damage control and NBC sensors will be presented on the colour VDU's by means of one or more specialized mimics.

The Damage Control mimics will be split into: general overviews, mimics showing one half of the ship, mimics showing one or more compartments etc. Also special features like kill cards, information on compartments, and location of equipment will be available.
The system data base or the ships central database will provide information about personnel, damage control teams and specialisations.
CAD features will be used to enable the operator to "compile" overviews of the action.
A graphic printer can "save" these plots for evaluation.
Also all the management tools to make a successful nuclear transit will be available including an integrated Radiac installation which enables the system to generate Intensity/Time plots without operator interference.
Since all systems can be assigned to all operator stations, it is also possible to control systems with a great influence on damage control from the NBCD control position (fire mains, ventilation, prewetting).
All information can also be presented in the operator station in the stand by MCR which will give the flexibility necessary to cope with larger scale incidents.

Miscellaneous

Other dedicated control systems will be installed for each air conditioning compressor, the refrigerating units, etc.
A lot of systems in the ship do not need dedicated control systems.
These systems mostly consists of pumps, pipelines, valves and tanks and will have "enough" sensors and remote controls to enable the "one" operator to control them.
This also means that a lot of routines will be simplified.
For instance filling up of service tanks will mostly be a remote controlled job.
Also the complex task of fuel replenishment will be carried out much more efficiently with all tank levels displayed real time at the operator/management positions.

CONCLUSIONS

The automation of the M-class frigate carries the burden of the following constraints:

- Costs;
- Time;
- Ships complement reduction.

Within these constraints an approach is made on a "design to cost" basis which will provide hardware and software necessary for a responsable operation of the M class frigate platform.
The systematic set up and the weighing of possibilities and solutions is not new, but under the present constraints there is no room for "nice to have".
Distinguishing between "nice to have" and "need to have" has, more than ever, become a dominant factor in system design.

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PROPULSION CONTROL IN THE SWEDISH M80 CLASS MINE COUNTERMEASURES SHIPS

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SYNOPSIS

The LANDSORT (M80) class mine countermeasures vessels embody propulsion devices new to warships. This paper reviews the selection of the M80 propulsion plant and the control requirements of the ship. The distributed microprocessor control system developed for the vessel, and its Man/Machine Interface, is described, and some practical experience of this novel controls application is discussed.

INTRODUCTION

Minehunting and minesweeping vessels have manoeuvring requirements quite unique among warships. Transit between base and operational area is performed in a similar manner to other vessels, but once on station the need is for very precise slow speed manoeuvring, creating the minimum possible signatures of noise, pressure and magnetism. Highly accurate position fixing is required both in respect of known hazards and to record accurately which areas have been surveyed and cleared.

The propulsion devices selected for mine countermeasures (MC) vessels tend to be correspondingly unusual, presenting new challenges to the warship control systems industry. The plant control of multiple azimuthing thrusters within the MC environmental restrictions is in itself unique, and the coordination of their outputs to give the desired ship thrust and turning movement is also new to warships.

The Royal Swedish Navy's LANDSORT (M80) class embodies radical selections of equipment. The control aspects of the propulsion plant selected set new and interesting challenges for control system design, which have been met by a distributed microprocessor system.

THE MINE COUNTERMEASURES SHIP MANOEUVRING TASK

The Swedish Navy's new M80 class mine countermeasures class of vessel is designed for both the minehunting and minesweeping roles. Both roles call for low underwater signatures and for the ship to be designed to withstand appreciable shock levels.

The minehunting role includes two operational modes, search and prosecution. For the propulsion plant, these can be described as the track keeping mode and the position keeping mode respectively. Track keeping is carried out at speeds between 1 and 6 knots, depending on the sea bed (the areas which best conceal mines being negotiated slowest). To minimise noise, suspect areas are searched by moving in the same direction as wind and waves wherever possible. Track keeping accuracy should be of the order of a few meters so that effective coverage may be maximised.

Any suspicious object detected in the search phase is then classified by sonar examination from two or more directions, and if it is still considered that it may be a mine, investigated by a remote operated vehicle. If it is confirmed as a mine, the object is then destroyed by a charge placed by the remote operated vehicle. During this prosecution phase, the duration of which generally is a little less than one hour, the ship is required to hover as little as two ship lengths away from the object. Deviations must, therefore, be kept small, and the propulsion plant noise must also be minimised. Minehunting sonar can compensate for variations in ship's heading, and provided the aspect to the mine is not within approximately 45° of the stern (which would necessitate the sonar 'looking' through the propulsors) the ship's head may be set in the direction which gives the easiest position keeping. In general, this means that the ship is headed into the wind and waves and the propulsor thrust is directed more or less due astern, with the added advantage that propulsor wash is well clear of the sonar transducers.

In many respects, minesweeping is the easier task. It involves a similar track keeping task to minehunting, aided to some degree by the course stability given by the sweep gear. The track recording is important but the track keeping accuracy can afford to be relaxed. The minesweeping role fixes the design of the propulsors, as the drag of the sweep gear will cause propeller blades to be most highly loaded, and cavitation should be avoided in this situation as the minesweeper may pass directly over mines.

SELECTION OF M80 PROPULSION SYSTEM

The propulsion services with which to meet the manoeuvring task are varied and novel. The selection of those appropriate to the M80 class ships was primarily made on the criteria of:

- Manoeuvrability, to meet the required track and position keeping accuracy

- Quiet operation, to minimise risk of triggering mines and to maximise sonar effectiveness.

The thrust amplitude is the most important variable to keep the noise as little as possible. The best way to do this is to adjust the heading of the ship, as within certain limitations this can be done without any adverse affects on the sonar. Achievement of the manoeuvrability requirements can thus assist in meeting the noise targets.

As long as the ship is maintaining speed over a certain limit, standard controllable pitch propellers and rudders will be able to fulfill the deviation requirements. However, as minehunting also includes position keeping, in this case a bow thruster is a necessity. A bowthruster, inevitably situated close to the sonar, will effect MC operation to some degree, as the sonar is sensitive both to the background noise and to irregularities in the water close to the antenna. This will put limitations to the operational use of the bowthruster.

Active rudders are an alternative which offer considerably better manoeuvrability and may obviate the need for a bowthruster, depending on the operation requirements for the ship regarding wind, sea and water current.

Another alternative is Voith Schneider cycloidal propulsors, which can deliver thrust in any direction. An installation of two such units was selected by the Swedish navy for the M80 (1). The operational environment around the Swedish coast is largely protected by islands and is non-tidal, so environmental forces are relatively small. Therefore the Swedish navy selected Voith Schneider propellers with no bowthruster. The VS propellers are used for all operation tasks and not only as an auxiliary propulsion during minehunting, hence rudders are not necessary. Voith Schneider propellers had previously mainly been used on merchant ships such as tugs and ferries but the Swedish navy carried out an extensive range of investigations (1). This included among other things a number of extensive cavitation tank tests, shock trials and magnetic ranging. This resulted in a modified propeller, where for example the standard transmission gear was replaced by a wormgear and the use of magnetic material minimised etc.

When selecting the size of the propellers and the type of blades, the most critical design requirement is cavitation free operation during minesweeping when the load on the blades is highest. For the minehunting operation the necessary thrust is very little compared to the minesweeping operation, which gives an excellent silent operation in this mode. Restrictions in the operational use must however still be implemented to prevent the propeller stream passing the sonar antenna.

The Voith Schneider propellers are each connected to two Saab Scania diesel engines, either or both of which can drive the propeller at any time. The transmission is via clutches and a vee belt combining/reduction transmission.

THE MAN MACHINE INTERFACE

For their merchant applications Voith Schneider developed a standard mechanical teleflex system, where the control for each propeller consists of a large lever for setting the x-pitch and a wheel for setting the y-pitch (x corresponds to the longitudinal and y to the athwartships direction). The wheel is of the same kind and size as for a standard steering gear. Engine speed in these installations is controlled by a similar lever as used for the x-pitch.

The Swedish navy carried out an investigation concerning the man-machine interface about 10 years ago, as minehunters were then in the program for building during the late 1970's. Different layouts were tested in a bridge simulator where Voith's standard was one, but with smaller controls.

Other layouts involved various different controls where the thrust direction was controlled separately for each propeller. The different control layouts were compared in different operation situations and as an optimal solution Voith's standard was selected, but with certain modifications as follows:

- Both levers and wheels to be smaller

- paralleling possibility for both wheels and levers to facilitate one-hand control of x-pitch and engine speed for both propellers and one-wheel for control of y-pitch for both propellers.

A single joystick control, where the movement is directly proportional to the total thrust amplitude and direction was an alternative which was considered for the M80 minehunters but was rejected. With only two propellers at the far aft end of the ship, the use of the joystick would be limited. For example a side translation of the ship would demand large thrust amplitudes and with almost opposite directions, which would create unacceptable noise levels.

The most difficult operation situation for the operator will be during a mine classification, as the ship should keep its position for a considerable time (almost an hour). This, depending on the weather, can be an almost impossible task for a human operator irrespective of the lay out of the control devices. The only solution to this problem is a fully automatic system where the endurance is unlimited, particularly as automatic systems have been shown to use lower thrust levels, thus minimizing noise (2).

Another result from the bridge simulation was to select instrumentation suitable for support of manual control of the ship, particularly as the experience with Voith propellers was limited. This kind of propeller has a complex relationship between lever-/wheel-positions and thrust amplitude and direction. For example if the lever for the x-pitch is set in the fully forward position (i.e. the thrust direction is forward and with full pitch) and the wheel is now turned to the fully starboard position, the thrust direction will change from forward to starboard direction, and the lever position will have very little influence on the direction. The maximum pitch also depends on the thrust direction as there is mechanical limiting curvature within the propellers. The thrust direction and amplitude also depend on the speed through the water, further complicating manual control.

To support the manual operator in his difficult task the bridge simulation showed that a thrust direction instrument would be valuable, as well as the x and y actual pitch.

When manoeuvring the ship under manual control, the most critical instrument is the steering indicator where the deviations from position or a track are presented. For the M80 minehunters this is double pointer instrument where the wanted position is in the middle and the true position is where the two pointers cross each other.

The man-machine interface resulting from these considerations is shown in Figs 1-4. Figure 1 shows the wheelhouse panel, on which can be identified the levers for x-pitch and engine rpm, the wheels for y-pitch, the cross pointer steering indicator, and the sub panels for propulsion display, engine control and back up emergency control. The sub panels are shown in more detail in Figures 2,3 and 4 respectively. The large meter at the top of the Propulsion Control Panel (fig. 2) is the resultant thrust meter mentioned above.

OTHER REQUIREMENTS ON THE PROPULSION CONTROL SYSTEM

The operator of the propulsion control system has a difficult task and it is essential to support him in all possible ways. As mentioned previously there are limitations in the operational use of the propellers either to avoid degradation of the sonar performance and/or to avoid cavitation. To relieve the operator of this additional burden, the propulsion control system should instead automatically compensate for these limitations.

The limitations consists of the following features:

- Thrust directions, where the water from the propellers is directed towards the sonar antenna, i.e. going astern, should be avoided.

- Changes in demands for pitch and speed should be controlled so that the rates of changes are limited.

- Other features which decrease the risk of cavitation.

Minehunters have to fulfill requirements on different signatures. One is the magnetic signature which puts requirements on the choice of building material for the ship. The M80 minehunters are solely built in glass reinforced plastic (GRP) (3) including both superstructure and hull. The complexity of the equipment is comparable to any other warship of this size. The electro-magnetic compatibility (EMC) requirements for the equipment on a steel ship are normally hard enough to fulfill, but in a GRP ship the problem has a completely different magnitude. As the GRP is transparent to electromagnetic waves the radiated interference is the dominating threat for degradation in performance or even for malfunction for the installed equipment. One main threat to the equipment is the short-wave transmitter, which could create electric fields with a magnitude of about 200 volts per metre. This puts very hard requirements on the vulnerability to radiated interference for equipment on the ship.

Furthermore on a steel ship the hull and superstructure makes a common reference plane for equipment installed at different locations in the ship. In a GRP a grounding system is established with cables and/or metal plate which in many cases only are for personal safety protection against electric shocks. The propulsion control system is located in different compartments, from the wheelhouse down to the engine room and over to the propeller room. These compartments are separated up to about 20 m with cable distances of up to about 40m, without having the common reference plane. This requires that the system is made independant of a common reference plane, and that an effective interference barrier is established between each unit and all external signals. Communications between different units are preferably made through optical fibre links where there is no problem of different reference planes and where each box is screened independently.

AUTOMATIC MANOEUVRING CONTROL SYSTEM

In order to implement the requirement for automatic control, the propulsion control system is required to accept a serial input from the navigation computer or similar to substitute for the normal lever and wheel inputs. For the M80 minehunters it was convenient to integrate the automatic propulsion control function in the combat information computer, where all input data necessary for the automatic control already existed. The addition of the automatic system required a new software module and only minor hardware changes to the combat information computer.

The reference for the automatic system is the search plan with its corresponding hovering points which is compared with the achieved position.

During track-keeping the input data will mainly consist of deviation from the track and deviations in the speed. For position-keeping it will be the deviation from a point and the deviation from the demanded heading. All inputs are fed through a Kalman filter which contains information of the corresponding previous data and the accuracies of all the sensors together with performance of the ship during track-keeping or position keeping. The filtered input data is fed into a linear quadratic regulator where the necessary forces are calculated which are translated into pitch settings on the Voith-propellers, and engine speeds. Before the demand data is fed to the propulsion control system there will, if selected, be two tests, one that checks if there is any risk of cavitation and one that checks if the thrust direction will interfere with the sonar antenna. If necessary modification will take place of the demands to comply with the tests.

The operation of the ship in the automatic mode is from the combat information centre, where the minehunting officer selects track-keeping or hovering mode. If track-keeping he also selects the demanded speed, and if position-keeping the demanded heading.

Development of the automatic system has been documented in reference (1).

M80 CLASS PROPULSION CONTROL SYSTEM

The M80 propulsion control system is provided by Hawker Siddeley Dynamics Engineering Limited. As shown in Figure 5, its principal components are two cabinets of electronics, each containing a rack mounted HSDE Dynalec 5000 system and a number of intelligent actuator controllers.

The Dynalec 5000 equipment is a range of rack mounted printed circuit boards designed for modular configuration of machinery control and surveillance systems. Its rugged construction was designed specifically for the marine environment, and has type approval from two of the major classification societies, Lloyds and Det Norske Veritas. Each configuration of Dynalec 5000 includes at least one Central Processor Unit (CPU) and several interface units to allow mixtures of digital, analogue (voltage, current and frequency) and serial data signals to be read in and output. The units interface with one another on a data bus formed by the backplane, or motherboard, of the rack system.

The CPU features an Intel 8085 microprocessor and memory in the form of Programmable Read Only Memory (PROM), Random Access Memory (RAM) and Erasable Programmable Read Only Memory (EPROM). Some

applications also use Electronically Erasable Programmable Re
Memory (EEPROM). The application program is held in the PROM
values which might need to be altered in the fine tuning
system are stored in EPROM or EEPROM. Variable data generated
operation of the system is stored in RAM.

The use of an 8-bit processor has been found to be appr
to the propulsion control and surveillance requirements o
cialised merchant ships and small warships. More powerful
systems are better suited to larger ships or applications w
very considerable auxiliary surveillance task is also set. Nc
in several years time the argument will be between
microprocessors and 32-bit microprocessors, but at present
technology seems to offer the best compromise of cost, complexi
capacity for many small warship propulsion control applicatio
single 8-bit processor can monitor and control up to approxi
150 channels. Multiple processors can be distributed around th
to deal with more channels, or, as in LANDSORT, achieve
integrity through dispersion.

The Dynalec 5000 software is of modular construction, an
many built in self checks. The failure philosophy is one of
set. Unprotected Dynalec 5000 units have been tested in a high
frequency interference environment, and these features have
shown to give an inherent resilience, since if one cycle of sof
running is corrupted, its output is most likely to be ignored.
next 'good' cycle, probably only fractions of a second later,
maintain control of the plant.

The wheelhouse cabinet (Fig 6) contains a single rack
electronics. Its Dynalec 5000 unit has the task of interfacing
the helmsman's console and the combat information computer, and
municating down a fibre optic link to the engine room cabinet. M
software tasks of the wheelhouse microprocessor are the drivin
displays including calculation of the resultant thrust vector
display to the helmsman.

The engine room cabinet (Fig 7) contains two racks of elec
nics, the upper of which is broadly similar to the wheelhouse u
This processor communicates with the wheelhouse unit via the f
optic links and interfaces with the plant actuator controllers.
noise and thrust limitation checks, and consequent modifications
the plant demands are performed in the engine room microproces
The engine room processor can also receive demands from a port
controller which can be used for manual control of delic
manoeuvring from various locations such as the bridge wings and
sweep deck. The lower rack of electronics contains a built-in si
lation facility, which allows the control system to be exerci
without running engines, and a completely independent back-up cont
system. The back-up system is hard-wired from the helmsman's cons
(Fig 4), and gives axial and athwartship thrust control for e
shaft in the event of failure of the main control system. Each
the cabinets contains a handset with keypad and alphanumeric displ
which can be used to interrogate the processor when fault finding.

Particular attention was paid to meeting the very high ra
frequency interference (RFI) requirements. Each cabinet is divi
into an RFI 'clean' area to contain the electronics and a lo

chamber which contains terminals, relays etc. All signals passing from one chamber to the other are routed via a distribution/RFI filter board to prevent noise being carried into the clean chamber.

Each intelligent actuator controller also contains an Intel 8085 microprocessor, and it too is designed to withstand the RFI environment. Each controller performs the closed loop control of pitch or engine speed, and includes rate limit controls, self checking facilities and feedback of achieved settings for display at the man machine interface. Two actuator controllers are shown in Fig 8, mounted in the deckhead of LANDSORT's Engine Room.

EXPERIENCE IN PRACTICE

The first of the M80 class ships, LANDSORT (Fig 9) has been at sea since early 1984. The manual controls have worked well, though naturally there were lessons to be learned when setting up such a novel system. The attention paid in the design to RFI protection has proved particularly successful.

It was thought that the handling of a Voith Schneider propelled warship might present particular problems, but in practice the ships operators have learned quickly and easily.

An example of unusual operation is the Voith Schneider performance map, which gives priority to athwartships pitch setting, reducing fore and aft pitch setting to near zero when large athwartship pitch values are demanded. In practice the operators have found this effect very easy to live with, and indeed consistent with their wishes.

The Voith Schneider athwartship pitch control wheels have 180° travel from maximum starboard to maximum port. There was some interest in how operators would get on with such coarse control, but in fact after the first few minutes of erratic course new operators soon attune to the sensitivity of the helm control. It is of note that a standard autopilot unit operates the controls quite satisfactorily.

The number of levers and wheels confronting the helmsman makes it difficult to manoeuvre the ship in the traditional manner, by oral commands from the officer of the watch (OOW) to the helmsman. In practice, when close manoeuvring is required, the operator is given authority to use the controls as necessary to achieve the result required by the OOW. The propulsion system has been used to hold the ship stationary across wind, though the large (opposing) port and starboard Voith Schneider power settings required make the ship noisy when so doing. The omni axial performance of the sonar means that when minehunting a favourable heading may be used to minimise noise when hovering but for confined manoeuvring it is reassuring to know that the ship can be held stationary at any attitude to a moderate wind.

The automatic control system will be added to the ship shortly, and its performance is awaited with interest.

ACKNOWLEDGEMENT

The authors acknowledge with thanks the help given to them by colleagues at Karlskronavarvet AB and Hawker Siddeley Dynamics Engineering Limited, and are grateful to the two companies and to the Royal Swedish Navy for permission to publish. Opinions expressed are not necessarily shared by KKrV, HSDE or the RSN.

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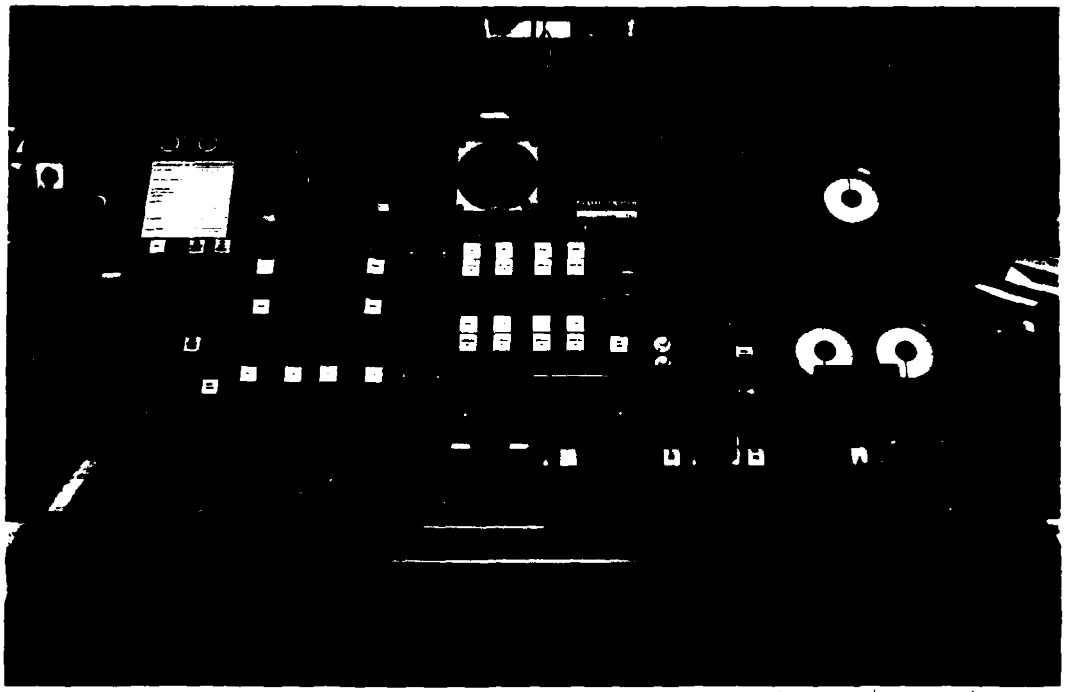

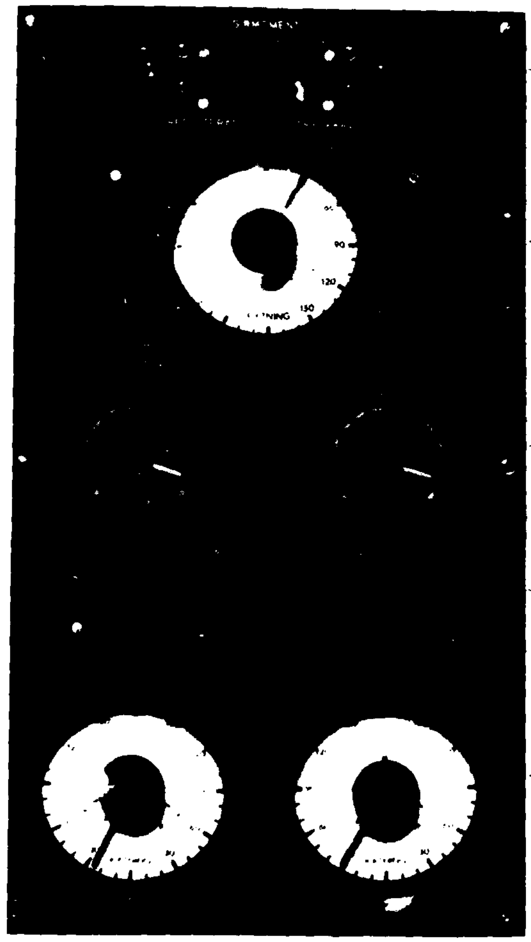

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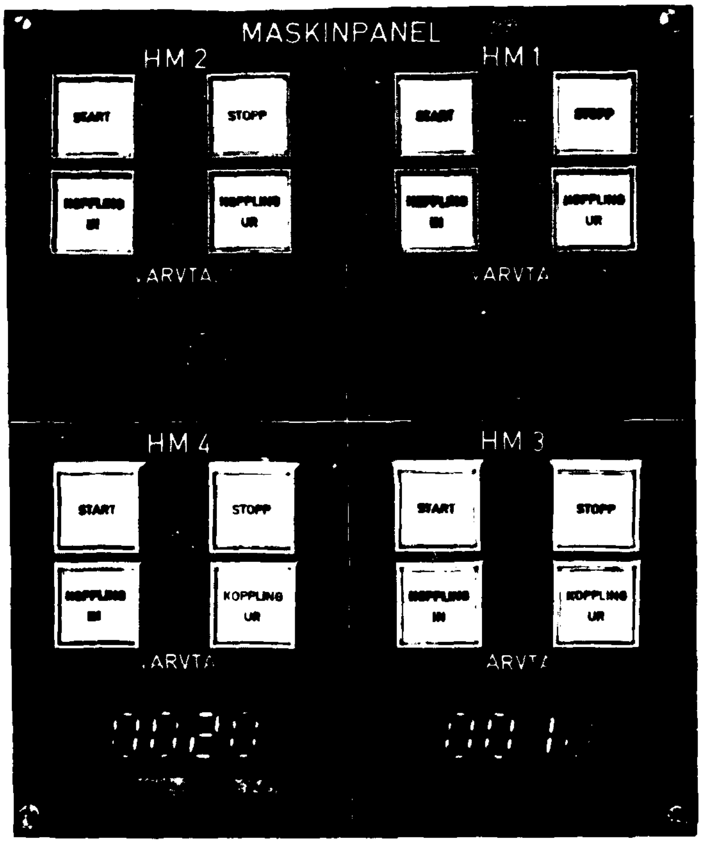
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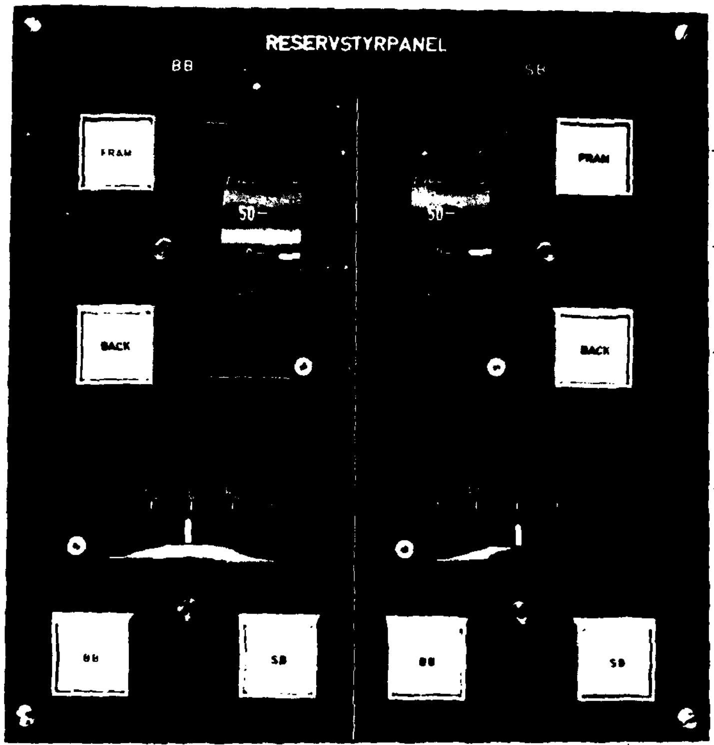
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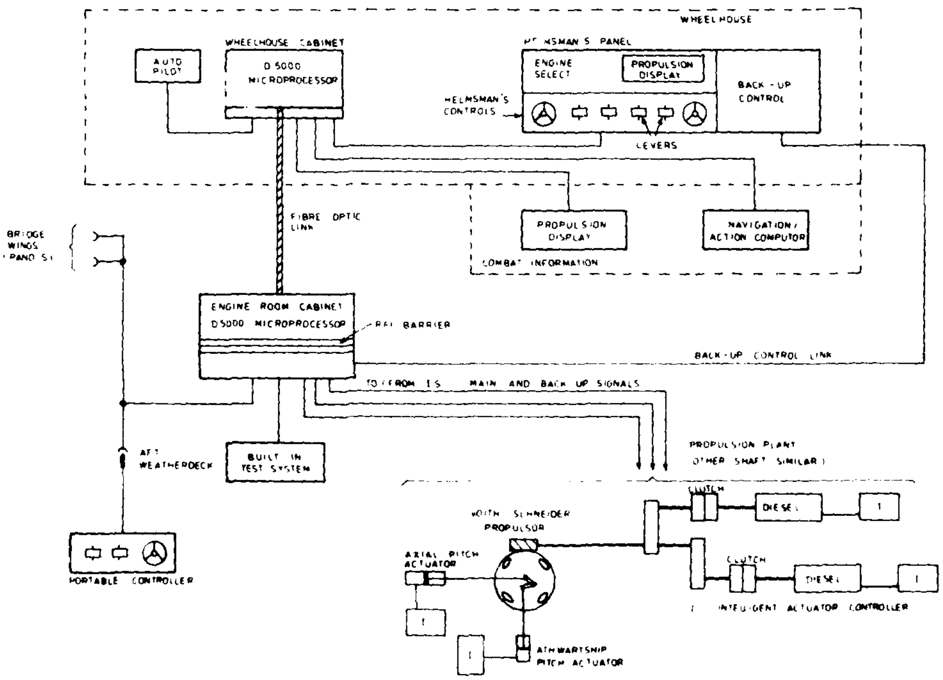

Fig.5 M80 Minehunter Propulsion Machinery Control System

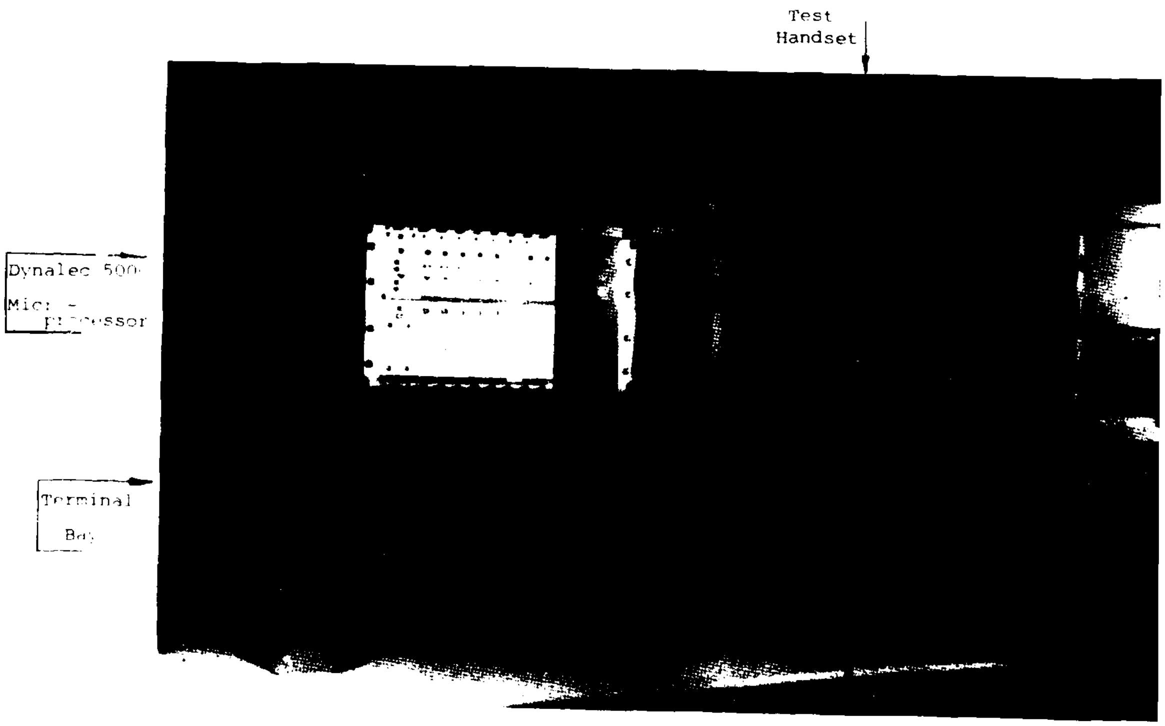

Figure [illegible] Wheelhouse Control System Cabinet (Photographed during construction).

Figure [illegible]: [illegible] Room Control System Cabinet, photographed during construction.

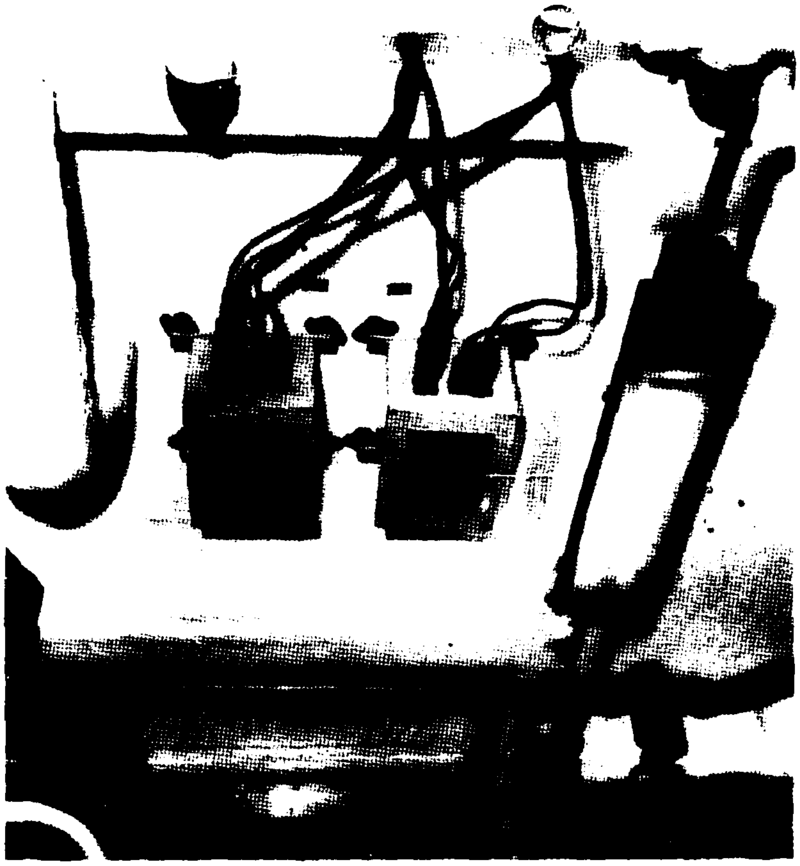

Figure [illegible] : Engine Actuator Controllers mounted in the Engine Room deckhead of 'LANDSORT'.

Figure [illegible] : M[illegible] class leadship 'LANDSORT'

PRACTICAL EXPERIENCE IN THE APPLICATION OF MICROPROCESSORS TO MACHINERY CONTROL AND SURVEILLANCE

by Paul H Sallabank
Vosper Thornycroft (UK) Limited

INTRODUCTION

The move towards the use of digital technology in the control and monitoring of Warship Machinery Systems has been stimulated by the promise of savings in both initial procurement and through life costs. One of the premises against which these savings are achievable is the utilisation, wherever possible, of hardware (and possibly software) from an already developed standard range.

Development of the standard hardware and software has been carried out largely as private venture within industry. Government sponsored development has also been conducted, mainly in specialised areas. For example, D86 is a Vosper Thornycroft Controls (VTC) private venture development and PASS is a joint YARD-MOD development (Reference 1 refers).

This paper considers some of the lessons learnt in applying developed and in some cases developing, hardware and software for real ship systems. It should be stressed that in each case, the hardware type has been specified at the outset. This being in contrast to the purist view which advocates software design first, followed by choice of hardware. Whilst this latter path provides the ideal technical solution, practical experience indicates that timescale precludes this approach and, in the author's view, it will not be the most cost effective solution.

To illustrate this view and a number of other relevant points, the Type 23 Machinery Control and Surveillance (MCAS) design is discussed later in this paper.

BASIS

The basis of this paper is an experience which spans almost a decade and is outlined in Fig 1. This experience reveals that the potential advantages forseen in Ref 2 and reviewed in Ref 3 can in fact be realised. For example, the Lurssen MCAS Project, involving remote control of the CODAG Main Machinery shown in Fig 2, 650 channel surveillance and full automation of auxiliary machinery, was delivered within 13 months of the order, and substantially recharacterised during STW and Sea Trials. This was achieved at roughly one half the cost of the predecessor technology, (dedicated analogue/hybrid electronics) and with no apparent operational disadvantages.

DIGITAL VERSUS PREDECESSOR SYSTEMS

As the use of digital technology and in particular microprocessors

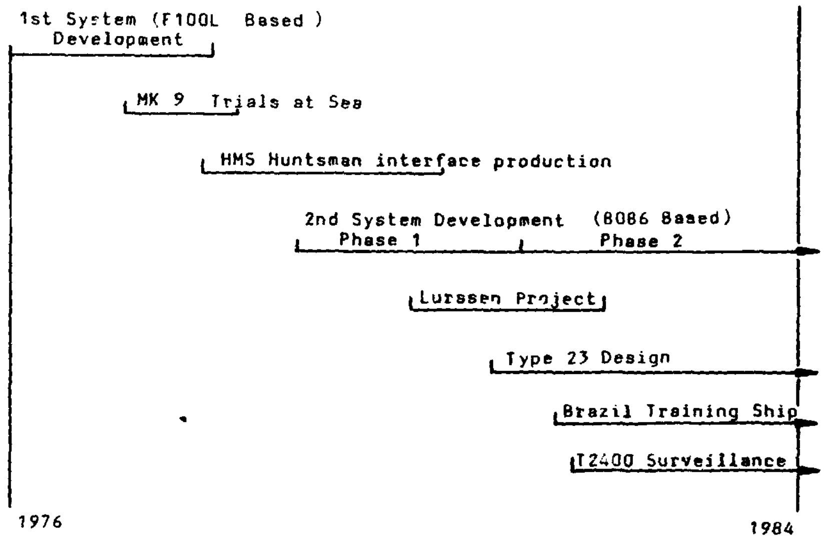

Figure 1 Basis

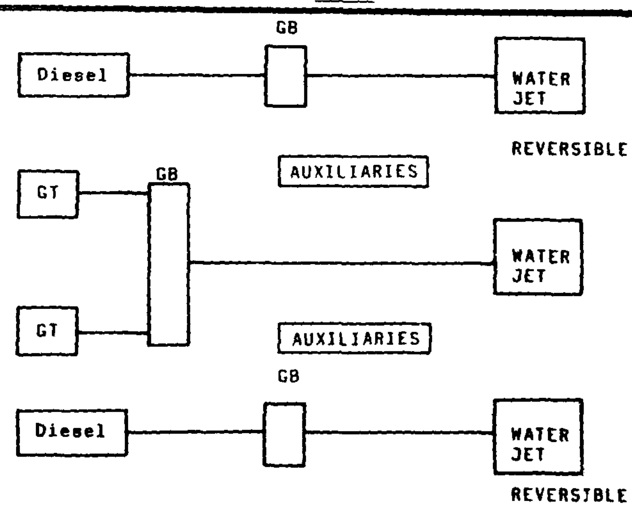

Figure 2 Lurssen Codag Main Machinery Configuration.

in MCAS systems is relatively new, comparisons with pre-micro systems are inevitable. The advantage/disadvantage comparison is well documented, (References 4, 5 and 6 for example) but when one becomes involved in the practical application the comparison takes on a different significance. Some examples follow.

Physical Size of the Electronics

To do the same job as the predecessor equipment, the electronics is of the order of one fifth the size. When coupled to a VDU based MMI this can lead to a significant under-estimate of the complexity of the system, particularly by the shipbuilder and ultimate customer.

Physical Size of the Interfaces

The size of the plant interface is unchanged as it is determined by the number of wires required. A trend towards drastically increased numbers of surveillance channels is evident. However, the cost in terms of interface size, weight and price (interfacing is expensive) must be clearly understood. This point is addressed again later in this paper.

Standard Hardware Limitations

Predecessor hardware, being designed to suit specific applications, was tailored to suit every requirement and interface. Standard hardware has limitations which may impact, for example, on the selection of transducers. This must be appreciated from the outset if a self defeating modification of the standard is to be avoided.

Functional Flexibility

A major advantage, long forseen and realised in practice, but beware, the digital system must not become a dustbin into which all the forgotten or "nice to have" after-thoughts get loaded.

The requirement to keep strict control over processor loading, memory size and software documentation, from day one of system design to completion of sea trials and beyond, is a discipline of paramount importance if all the initial design requirements are to be met. In particular, executing functions in dedicated, purpose-built hardware, where appropriate, remains an important option for the system designer.

However, advantage should be taken where a digital implementation can provide operational improvement. For example, rather than blindly following established control techniques alternatives which may offer improvements in fuel economy and/or manoeuvrability must be considered. Solutions which were prohibitively expensive using predecessor technology may well be highly cost effective with a digital system.

Technology Gap

The specialisation necessary in the development of digital hardware and the production of high quality software, leads potentially to a growing gap in understanding between hardware/software specialist engineers and their applications or system engineering counterparts. This applies within the controls industry, within shipbuilding, and within navies. The speed of technological advance is widening this gap at an increasing rate. The Systems Engineer finds himself in the uncomfortable position of straddling this gap and consequently needs increasing management support. The success of digital MCAS systems is much more dependent upon the quality of Project and Engineering Management than were the predecessor systems.

Configuration

Largely due to the greater inherent compatibility of multiplexing (in the form of serial data transmission) with digital systems, when compared to predecessor systems, the former provides considerable flexibility in the configuration of equipment. A distributed system, with data collection and plant associated control functions implemented locally, and data processing and system control implemented remotely is completely feasible.

However this flexibility of configuration is such that the system engineer is now spoilt for choice. Differences in configuration options in terms of cost, vulnerability, reliability, etc, are often slight but nevertheless tempting to debate. Indeed it is surprising how many "experts" at configuring systems emerge during system design. The criteria and rules and to an extent experience, necessary for the speedy resolution of configuration need strengthening in order to:

(a) Speed up the system design process

and

(b) Give greater confidence in the design decisions.

Regarding this latter point, it seems that improving confidence in the integrity of serial data transmissions and clarifying the cost and benefit equation will remove a great deal of the debate in this area.

Certainly the best rules and criteria available must be established at the start of a project, before options are evaluated.

SYSTEM DESIGN DECISIONS

Fig 3 shows a simplified decision tree for the basic MCAS system design process against a specific ship design. The diagram is simplified for clarity, in practice many loops being necessary to achieve the most cost effective solution.

The inputs to the process fall into three categories, namely:

(a) Design requirements for a particular ship, usually supported by feasibility work.

(b) Specification of the basic standard hardware to be used and rules to be applied to software.

(c) General standards applicable to engineering, quality, documentation etc, (not shown on the diagram).

The most significant point to note is that by specifying proven

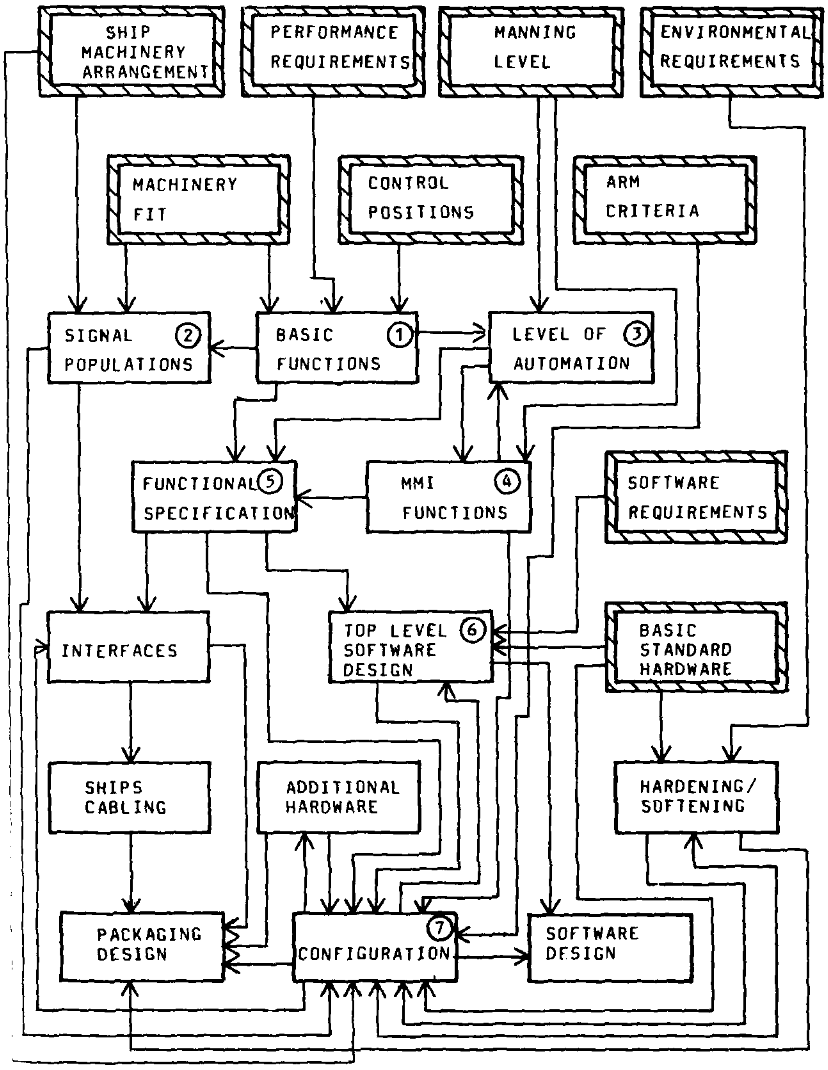

Figure 3 Decision Process (Partial)

standard hardware its development is decoupled from the ship design programme, provided that the standard hardware is adequate. This has the effect of reducing risk as proven hardware can be specified as well as prospectively reducing the duration of the design and build programme.

A description of the various 'decisions' identified in Fig 3 is given below.

Basic Functions. Decides the fundamental control and monitoring requirement inherent in the chosen machinery fit, ship performance requirement and control positions. Some of these functions will be specified by the machinery suppliers or decided from experience.

Signal Populations. A preliminary decision on the location, type and density of signals at the boundary of the plant manufacturers extent of supply.

Level of Automation and MMI Functions. These two areas of decision making are taken together as they are both fundamentally dependent on the manning requirement.

The level of automation must be decided based on the capability of an operator (speed, dexterity, reliability etc), and the number of operators available under different ship states.

The MMI functions are decided by considering what information and facilities are required by:

(a) The operator to respond to orders and maintain safe operation of machinery, ie continuous information.

(b) The operator to identify and recover from a failure.

(c) The operator or maintainer to assess periodically the condition of plant and equipment, ie information only required periodically.

(d) The maintainer to diagnose and repair a failure. This may determine any limitation on what is repairable at sea although the major consideration in this respect will be inherent in the design of the standard hardware.

All these aspects fundamentally affect the system input requirements, data processing requirements, control strategy and MMI format.

It is essential that proper workload and ergonomic assessments are carried out to validate design in this area if uncontrollable situations or unnecessary complexity are to be avoided.

Overall Functional Specification. This specification forms the basis of communicating the application requirements to specialists for implementation. It also provides the means for validating decisions taken by allowing machinery suppliers and ship design authorities to comment on its acceptability or otherwise.

Top Level Software Design. The software specialists interpretataion of the functional requirements can be gauged by this document. Also decisions regarding processor functions and loading and memory size are reflected here as iterative loops involving the configuration design.

Configuration. This represents the most complex of all the decision making processes and merits a paper in its own right. The process requires inputs from previous decisions as well as ship design information. In particular ARM and vulnerability criteria are brought into the equation. With so much data, and so many trade-offs, it is not generally possible to examine the cost/benefit of every option. Some qualitative judgements must be made in such areas as vulnerability.

Experience has shown that the final decision on configuration must be a long-sighted one, as the decision must be made before the detail of ship system design in some areas is finalised. The decision must anticipate some growth in both signal population and functions in areas where design is least firm. A structure that will allow the addition of data links/bus spurs and increased data traffic is essential. The degree and more critical areas can only be judged on the basis of experience. One thing is certain, without the application of experience in making this judgement, the configuration chosen will ultimately turn out to be the wrong one.

Interfaces. The control of interfaces has always been a major task in the MCAS system design. Digital technology has not made it any easier. Indeed it has introduced two further problems for the unwary.

Firstly, the use of standard hardware limits the range of interface characteristics. It is vitally important that plant suppliers and those responsible for any transducers are made aware of the limits at the earliest opportunity in the ship design.

Secondly, the space requirements for interfacing now occupy a much larger proportion of the total equipment volume than in predecessor equipment. For example, in predecessor systems the interface occupied approximately 20% of total volume, whereas in digital systems it occupies approximately 60%. As a result, equipment dimensions are much more sensitive to the interface size and as a consequence, changes (which are always an increase), carry greater penalties, even though the electronics and software may be less sensitive in this respect.

THE RN TYPE 23 DESIGN

The Machinery Control and Surveillance System for the Type 23 is required to carry out the following functions:

- provide remote control of all main and some auxiliary machinery from the SCC.
- provide remote surveillance of all main and auxiliary machinery from the SCC.
- allow local control of all main and auxiliary machinery from adjacent the plant.

The distribution of machinery and equipment through the relevant spaces and compartments is shown in Fig 4.

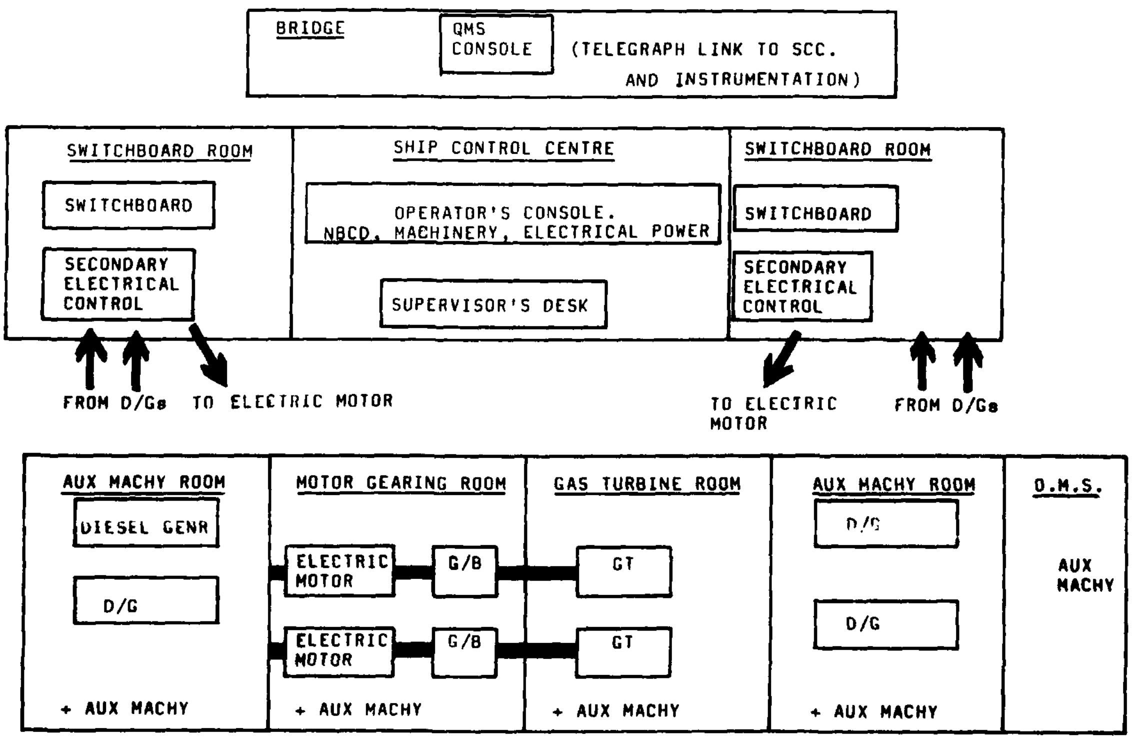

Figure 4 T23 Machinery and Equipment Distribution

Functionally, the requirements have been sub-divided into the following sub-systems:

- Propulsion Machinery Control
- Auxiliary Machinery Control
- Primary Surveillance
- Secondary Surveillance

The Ship Control Centre (SCC) is the location for all the principal remote control and surveillance MMIs. These include main and auxiliary machinery, electrical power generation and distribution and HQI functions. These facilities are integrated into an operator's console and a supervisor's desk. Bridge control is not provided.

The requirement is to produce an MCAS system for service in a typical warship environment that meets specific ARM targets and allows safe operation of a complete machinery fit by a reduced watch (when compared with current similar vessels). These requirements to be achieved within tight cost constraints.

Following feasibility studies and outline ship design, Vosper Thornycroft (UK) Limited Controls (VTC) were selected as Lead Controls Sub-Contractor and placed under contract to Yarrow Ship-Builders Limited (YSL). Inherent in the choice of VTC was the selection of D86 as the standard hardware range. With respect to the Decision Process (Fig 3) the Project is currently concluding ship cabling detailed definition and packaging design details as well as developing software and interface details at the lower levels.

Before considering individual decision processes and the impact of experience on particular decisions, it is worthwhile reflecting on the status of the standard hardware.

Hardware Status

The objective of decoupling hardware development from ship design was perfectly valid at the time D86 was chosen. The vast majority of the hardware required for T23 was developed and proven, having been in service now for well over a year.

However, the component industry finds it necessary to continuously improve devices such as memory chips at an alarming rate. Consequently, the "standard" can be overtaken, as last years devices get replaced on the suppliers shelves by this years improved versions.

The substitution of new devices for old therefore becomes a continuous development process with, in the main, a benefit to performance. It should be stressed that this benefit may come as a bonus, eg by giving greater memory capacity on a single board, but it cannot be relied upon.

The result is that the capability and characteristics of the 'standard' may change during the system design process. The System

Engineer must be kept fully informed of potential changes in this respect. He must have the ability to request or decline an update to the standard for his application if he is to keep control of the system design and its costs.

Automation and MMI Decisions

The following options were identified as means of validating design decisions in this area:

- evaluate at sea
- evaluate on a simulator
- evaluate on a full-size mock-up
- evaluate on scale models and drawings

These options relate to the evaluation of operational aspects. From the manufacturers point of view, evaluation of construction, installation and setting to work are also important if costs are to be kept to a minimum.

At the start of the project, two decisions were taken which fundamentally affect the approach to be adopted.

(a) A set of equipment would be evaluated by MOD against a simulation at well in advance of First of Class sea trials.

(b) Primary surveillance would be hardwired (as opposed to multiplexed) between the plant and dedicated instruments and indicators in the SCC.

The decision to evaluate thoroughly against a simulation is enabled by the use of digital technology. The timescale to produce a system s now short in comparison with shipbuilding timescale.

However, the second decision results in a considerable amount of console hardware which will be expensive and time consuming to modify drastically as a result of evaluation. Obviously, were the MMI software based, ie utilising VDUs and keyboards for the majority of display and control functions, a different equation would result. It is not the purpose of this paper to debate the merits of quantum change in MMI technology versus Darwin.

The following programme was developed jointly by MOD, YSL and VTC:

- Analyse operator tasks to achieve ergonomic grouping of facilities.
- Evaluate design on a full scale mock-up using personnel with operating experience (touch drills).
- Evaluate constructional aspects by:

  (a) Full scale mock-up
  (b) Full size console section

- Allow adequate period for system test at factory - the correction of mistakes being cheaper here than in the field.

- Make every effort to achieve simulation based evaluation early with respect to ship programme.

In addition, particular attention is being given to VDU page and printer formats, as a paperwork exercise during design.

It is considered, in the light of experience, that this process is producing the most cost effective design of MMI and supporting automation, with the minimum risk of operational difficulty or major modification post design.

Configuration Decisions

The configuration chosen is illustrated in Fig 5.

A distributed philosophy has been adopted for both control and secondary surveillance.

As a means of keeping costs to a minimum some control and surveillance functions are carried out by a single processor. This has been achieved without transgressing ARM targets.

The distributed D86 units are identified as either Data Collection Units (DCU), or Control and Data Collection Units (CDCU). Each unit comprises standard D86 boards including processor board, memory board, diagnostics board, serial data board(s) and a selection of input/output board types. In all a total of 14 board types are used throughout the system.

Multiplexing is achieved with Serial Data Links (SDL) using an HDLC protocol. This provides a relatively cheap and simple data transmission.

A simple star configuration was chosen in preference to the multi-drop linear bus or ring options. The major reason behind this decision was the objective of minimising the communications software complexity. Experience had indicated the dangers of overloading a system primarily intended for control and surveillance with an unacceptably high communication overhead in the software. Reference 7 discusses this topic in more detail.

The transport of data requires a different approach if the philosophy of bussing all control and surveillance data is to be adopted. This is not to say that HDLC would not cope, but experience says that the software risk would certainly be increased significantly. A walk before you run approach is therefore advocated.

A major criterion in the allocation of processors around the system is their prospective loading and memory size. A target of less than 50% loading for each was set, based on the Level 1 software design. In most cases the loading was significantly less than 50%.

On completion of Level 2 software design, and with some growth in requirements, we find that with one exception all processor loadings are still at or below the 50% mark. Memory size require-

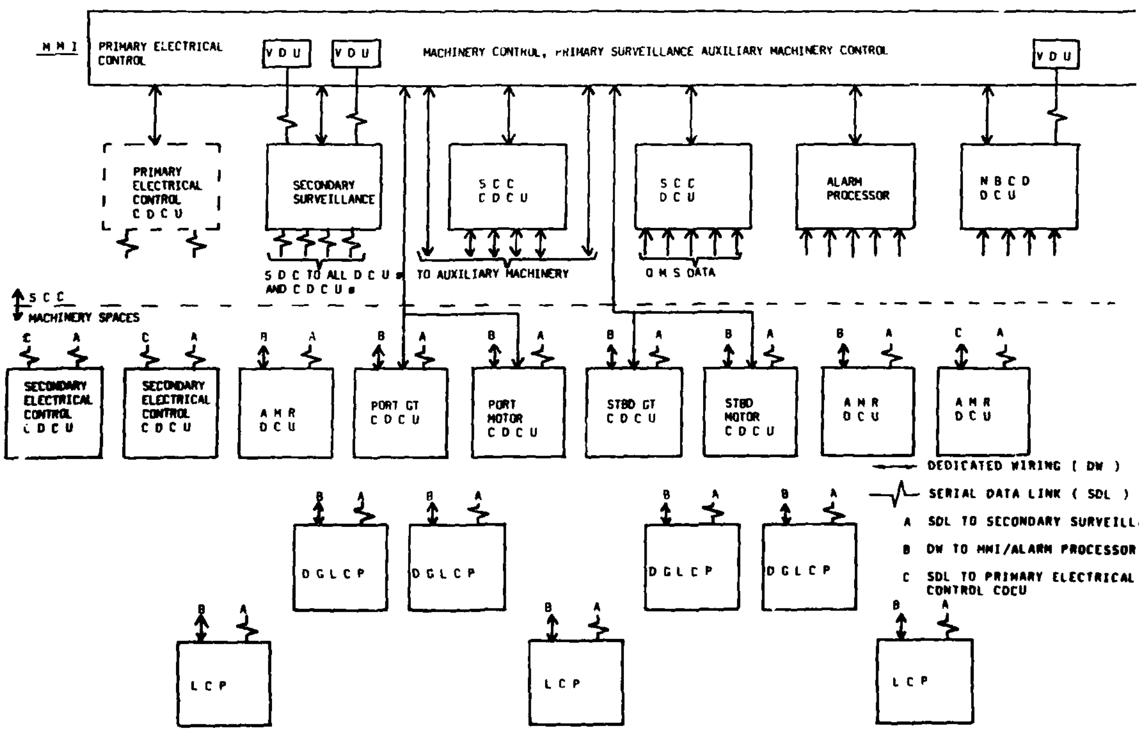

Figure 5 System Configuration

ments have increased more significantly but still remain at a safe level (60%). Interestingly, the growth in memory chip capacity, since the design began, has effectively widened the margin by 25%.

Growth in memory requirements during software design remains the most difficult area to assess. There does not appear to be at present a margin that can be consistently used with confidence. Plainly the software specialists need to do more soul searching!

Propulsion Control

The implementation of propulsion control is shown in Fig 6.

Distributed control was chosen in order that plant associated functions and the plant interface could be implemented locally. The connections necessary between the plant associated CDCUs and the central shaft control MMI are consequently so few that hardwiring was concluded to be adequate and cheaper than using multiplexing.

The CDCUs do not execute all plant associated functions. In particular, a number of electric motor control functions are carried out in the motor controller using analogue technology. There are both technical and contractual reasons which lead to this decision. This is a good example of the appropriate use of technology.

Auxiliary Machinery Control

The implementation of auxiliary machinery control is shown in Fig 7.

Where complex items of auxiliary machinery are controlled, local CDCUs are used with SDL links to the SCC. These links carry both control and surveillance data.

Where simple items of auxiliary machinery are controlled, hardwiring is used. In some cases, the automation of several items of machinery which are in the same auxiliary system but distributed around the machinery spaces is carried out by the SCC CDCU.

Secondary Surveillance

This system is currently handling 1000 channels of data and generating VDU page formats and printer formats.

The configuration of the secondary surveillance system is effectively that shown in Fig 5 as all remote units carry out data collection functions and pass data via SDLs to the central system. The central system is sub-divided as shown in Fig 8.

The communications processor was deliberately added at an early stage in configuration design in order to allow a large margin for growth. In particular additional SDLs were anticipated. The number of SDLs has in fact increased by 50% over the last 12 months and the communications processor loading is currently at 50% (level 2 software design completed).

CONCLUSIONS

The design of the T23 MCAS system reflects a collation of

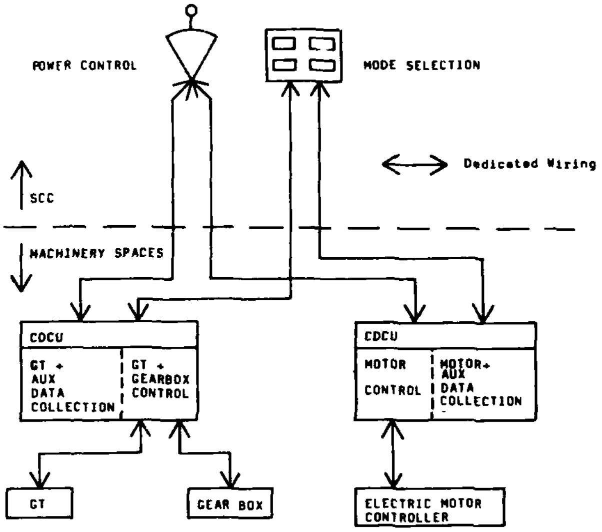

Figure 6 Type 23 Propulsion Control Configuration (1 Shaft Set)

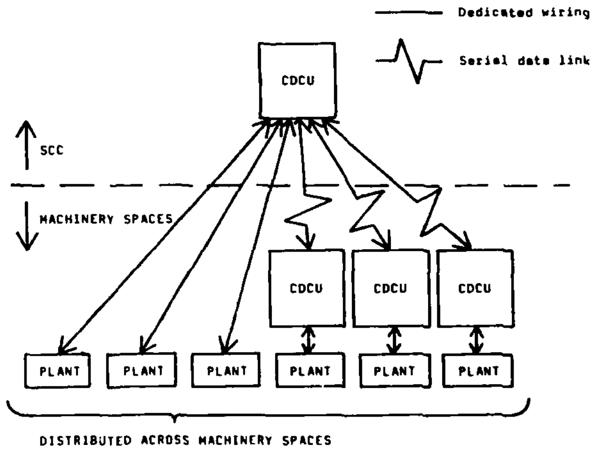

Figure 7 Type 23 Auxiliary Machinery Control Configuration

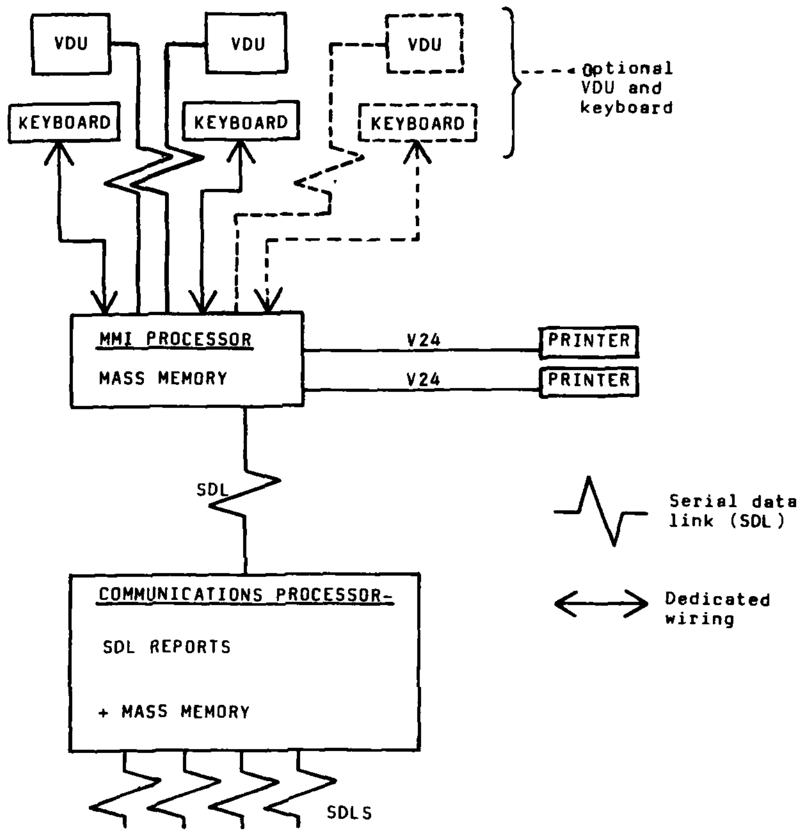

Figure 8 Type 23 Secondary Surveillance Central System

experience in the development and application of microprocessor based equipment. There are, in particular, four lessons which stand out above all others:

1. Maintain close control of the software and hardware standard, document it well and be judicious in following the technology trends.

2. Ensure that applications experience goes into the initial design, particularly in the context of recognising critical areas of likely growth.

3. Establish the rules that govern decisions before you attempt to make the decisions.

4. Provide strong management, particularly in support of the System Engineering function.

The technology itself is well established. Provided the lessons are well learnt, the application of microprocessors to machinery control and surveillance systems will achieve the benefits forseen nearly a decade ago.

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A CLASSICAL APPROACH TO A MICROPROCESSOR BASED PID AUTOPILOT DESIGN

by L P Luk

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ABSTRACT

Despite various recent developments in "adaptive" autopilots employing modern control theory, conventional PID autopilots are still dominant on board ship. The main drawback with these "traditional" systems is their lack of adaptability. Nevertheless, the PID algorithm is generally accepted as being adequate for most control applications. Additionally, advances in microelectronics over the past decade have provided tools which have had a major impact on the approach to the design of control systems. This emerging technology has facilitated the application of a microprocessor based PID system to the "autopilot" problem, and this approach was adopted.

In this paper, the concept of an analogue approach to the design of an 8-bit microprocessor based autopilot is presented. Specific topics discussed include : optimum setting of the autopilot; use of the bilinear z-transform method in converting the control algorithm from analogue to digital; and the practical problems associated with hardware and software design.

Through dynamic testing, with the aid of a simulated "Mariner Class" of cargo ship mathematical model, the performance of the microprocessor based autopilot was examined and compared with that of its analogue counterpart. An investigation into the effectiveness of the microprocessor based system under different environmental conditions was also made.

It is hoped that this feasibility study will show that the application of classical control theory is adequate for the design of microprocessor based control systems for a ship's autopilot. This has a particular appeal in that classical control theory is well developed and more familiar to the majority of control engineers.

INTRODUCTION

The trend towards the use of digital control, particularly following the introduction of microprocessors, has brought a new approach to controller design, in which digital techniques, based on optimal control theory, are applied from the outset of the design process. An alternative approach, however, is to use those "tools" previously associated with the design of analogue systems and, when the design is complete, to apply a "mapping" process to convert the analogue design into a programmable digital control algorithm. Methods of converting analogue networks to digital networks can be divided into three categories : (i) Approximate Integration techniques, including Rectangular Integration, Trapezoidal (bilinear or Tustin) Integration and Simpson's Rule. (ii) Transient Response Matching techniques, including the Impulse Invariance, Step Invariance and Ramp Invariance methods. (iii) Matched Z-transform. Because of its simplicity coupled with the accuracy in the conversion of analogue to digital algorithms, the bilinear z-transform method was adopted in this study.

Since the early 1950's, theories of proportional plus integral and/or derivative control have been implemented in ship autopilots. During the last decade, advances in modern control theory have made a radical impact on the design of autopilots, in this connection, names like "adaptive autopilot", "self-tuning autopilot" and "optimal control autopilot" have emerged [1-5]. Besides the modern approaches, efforts have been made in applying some forms of adaptive action, based on classical control theroy, in order to reach an optimum control criterion for autopilots [6,7], and an investigation into such an approach forms the basis of this paper.

One of the tools employed for this study was a ship steering simulator, constructed mainly by three under-graduates [8-10] of the Department of Maritime Studies of UWIST. The simulator comprises a ship model unit, an analogue PID autopilot plus steering and rudder unit, and a sea/wind disturbances simulation unit. The digital PID algorithm was implemented on a Rockwell AIM-65 microcomputer system. The digital control unit was completed by adding an analogue-to-digital (ADC) and a digital-to-analogue (DAC) converter units, plus bias adjusters. The microprocessor based autopilot was tested using a mathematical model of the dynamics of a "Mariner Class" of cargo vessel and the results achieved were compared with those for equivalent analogue system to demonstrate the viability of the design.

SHIP MATHEMATICAL MODELS

In order to achieve effective control of a system, its transfer function as represented by a mathematical model has first to be constructed. A good model in fact forms the basic requirement for any "adaptive" system. The dynamic behaviour of a ship is very complex. It experiences six degrees of freedom, moving along and rotating about three mutually perpendicular axes. However, if the ships' motions are assumed to be confined in a horizontal plane, only surge, sway and yaw motions need be considered, thus simplifying the problem. Nomoto [11] derived a second order differential equation relating yaw angle (ψ) to rudder angle (δ):

$$T_1T_2\dddot{\psi} + (T_1 + T_2)\ddot{\psi} + \dot{\psi} = K(T_3\dot{\delta} + \delta) \qquad (1)$$

where K, T_1, T_2 and T_3 are parameters related to the hydrodynamic characteristics, mass and speed of the ship. Transformed into Laplace domain, (1) becomes:

$$\frac{\dot{\psi}}{\delta}(s) = \frac{K(1 + T_3s)}{(1 + T_1s)(1 + T_2s)} \qquad (2)$$

This linear model will only hold on the assumption that the speed of the ship remains constant during manoeuvres and the rudder angles are small (say not exceeding ± 5 degrees). As a result, Nomoto's model can only represent the course-keeping characteristics of stable ships.

With large rudder angles, non-linearities are introduced, particularly with unstable ships. Bech [12] modified Nomoto's equation by consolidating these non-linearities into a value $H(\dot{\psi})$ thus deriving the equation:

$$T_1T_2\dddot{\psi} + (T_1 + T_2)\ddot{\psi} + KH(\dot{\psi}) = K(T_3\dot{\delta} + \delta) \tag{3}$$

$H(\dot{\psi})$ is generally determined by the Reverse Spiral Test [13] for an unstable ship, or in cases of stable ships, through the Dieudonne Spiral Test [14].

In order to derive ship dynamic models in recent years, alternative approaches have been developed [15,16]. However, the Nomoto and Bech models are still widely used for autopilot design, ship design and prediction of ship manoeuvres [17]. Mainly due to its simplicity in circuit construction for a simple analogue ship model simulator, the Nomoto model is employed for this study. The ship model under consideration is a "Mariner Class" of cargo vessel. The transfer function of the vessel is given as [12]:

$$\frac{\psi}{\delta}(s) = \frac{0.052(1 + 25s)}{s(1 + 14.4s)(1 + 100s)} \tag{4}$$

SHIP STEERING CONTROL SYSTEM

A ship steering control system basically comprises an automatic pilot and a hydraulic-operated steering unit.

The Autopilot

The role of an autopilot in a ship steering control system is that of a servomechanism controller. As mentioned, despite different types of "adaptive" autopilot having been developed recently, conventional PID autopilots are still dominant on board ship. In general, this kind of autopilot is in the form of a "real" or interact PID controller, i.e. one with proportional plus integral plus phase-lead control. The transfer function of such autopilots for a rudder demand output (δ_d) to a heading error input (ψ_e) is given as :

$$\frac{\delta_d}{\psi_e}(s) = \frac{K_r(1 + K_{cr}T_{cr}s)(1 + T_{ph}s)}{T_{ph}s(1 + T_{cr}s)} \tag{5}$$

where the parameters and typical range of their values as given in [8] are:

K_r = rudder gain (0.5 - 3)
K_{cr} = counter rudder gain (1 - 9)
T_{cr} = counter rudder time constant (3.5 - 28 seconds)
T_{ph} = permanent helm time constant (100, 200, 400 and ∞ seconds)

A microprocessor based autopilot was also built around this transfer function and a comparison between the performance of the analogue and digital autopilots was effected.

Steering System

Most deepsea vessels today are mandatorily fitted with a dual electro-hydraulic steering system. This system is basically a closed-loop mechanical servomechanism consisting of an amplifier unit, a telemotor/relay unit and a steering gear unit. To derive a transfer function representing the overall dynamic characteristics of such a system is very complicated. Firstly, the rudder does not rotate at a constant rate over its entire operating range. Secondly, non-linearities of an relay-operated system further add to the complexity in analysing its dynamic behaviour. However, for small control amplitudes, such as those for course-keeping stability analysis, the transfer function of the steering gear can be approximated to a first order system according to Bech [12] as:

$$\frac{\delta_a}{\delta_i}(s) = \frac{1}{1 + T_r s} \qquad (6)$$

where T_r = 2 to 4 seconds

In recent times, the design of steering system has become an integral part of the efforts directed towards improving steering performance and fuel economy [18]. Nevertheless, Bech's model is still widely accepted for steering system analysis. It can be further shown [19] that since its time constant is relatively short as compared to the ship's dynamics, it can be regarded as "far-off" poles and will have little effect on the system design which is based on the "dominant" poles and zeros.

OPTIMUM SETTING OF SHIP AUTOPILOT

In recent years, many studies have been devoted to the optimum steering of ships. Much of this work has been enhanced by the advances in control theory (modern and classical) and in microelectronics technology. Apart from safety considerations, rapid increases in fuel prices in the last decade have lent some urgency to the search for better control in ship steering to improve fuel economy. In order to achieve an optimum setting of the autopilot, a performance criterion has first to be defined. Unfortunately, as yet, no clear and generally accepted definition is available.

It is an International navigational rule of the road that when changing course, particularly to avoid another vessel or some other navigational hazard, safety is the dominant factor. In this case, minimum overshoot coupled with a reasonable rising time and a constant rate of turn are desirable along with precise course keeping. A completely different situation arises when the ship is in open seas. The performance criteria will be dominanted by fuel economy rather than by accuracy in steering and fast response. Minimum rudder drag leading to a reduction in propulsion losses is desirable. However, it has been pointed out that too little rudder movement can result in elongation of the distance travelled thus offsetting the gain in fuel economy from reducing drag. Furthermore, different settings of the autopilot may be required when the ship is under different conditions of trim, at different speed, and when being influenced by various weather conditions, i.e. windage and swells.

Apart from the general criteria mentioned above, there have not been many specific studies relating to course-changing criteria. For course-keeping

Koyoma and Motora [20] first formulated a performance index based on the increased resistance due to rudder motion, weighted against the increase in distance travelled due to course errors:

$$J = \frac{1}{T}\int_0^T (\Delta\psi)^2 + \lambda(\delta)^2 \, dt \qquad (7)$$

where $\Delta\psi$ is the heading error
δ is the rudder angle
λ is a weighting factor

This semi-empirical criterion has been widely employed as the basis of many later studies involving optimum setting of autopilots [21-23]. Using transfer function techniques, a method was investigated by the author [19] from a standard-model-matching approach, for tuning the autopilot. This method was based on the philosophy that if the overall transfer function of a control system could be "moulded" into a standard form, its dynamic responses, in both the time domain (such as rise time, settling time and percentage overshoot) and the frequency domain (such as phase and gain margins), could be predicted. The standard forms envisaged were a second order model and a third order coefficient plane model.

Taking the "Mariner Class" of cargo vessel as an example (equation 4), the autopilot parameters (considering the phase-lead element first) should be:

$$\frac{\delta_d}{\psi_e}(s) = \frac{K'(1 + 100s)}{(1 + 25s)} \qquad (8)$$

Hence the overall closed-loop system becomes:

$$\frac{\psi_a}{\psi_d}(s) = \frac{1}{1 + s/0.052K' + 14.4s^2/0.052K'} \qquad (9)$$

This is in a standard second order model form. For $K' = 0.35$, then the damping ratio $\zeta = 1$ and the undamped natural frequency $\omega_n = 0.035$ rad/sec. The response to a step change in course is shown in figure 1.

Effects of Permanent Helm Control

An important factor in the design of autopilot settings which most studies in this area tend to neglect is the effect of the integral (I) control. In fact I-control plays an important role throughout the entire range of the dynamic response of the system. Taking the "Mariner Class" of cargo vessel as before and applying the standard-model-matching method in tuning the PID controller. The overall open-loop transfer function becomes:

$$G(s)P(s) = \frac{0.0182(1 + T_{ph}s)}{T_{ph}s^2(1 + 14.4s)} \qquad (10)$$

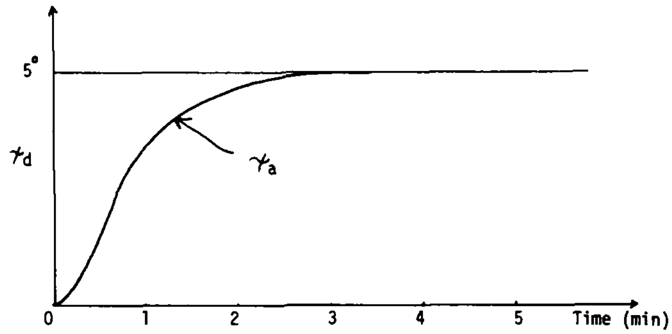

Fig. 1 Response to a Step Change in Course with No I-Control

On closing the loop, equation 10 becomes:

$$H(s) = \frac{1 + T_{ph}s}{1 + T_{ph}s + T_{ph}s^2/0.0182 + 14.4T_{ph}s^3/0.0182} \qquad (11)$$

This is in a standard Type II Coefficient Plane Model form [24].

(i) For T_{ph} = 100 seconds

$$H(s) \sim \frac{2.3(s/0.023)}{1 + 2.3(s/0.023) + 2.9(s/0.023)^2 + (s/0.023)^3} \qquad (12)$$

(ii) For T_{ph} = 200 seconds

$$H(s) \sim \frac{3.7(s/0.018)}{1 + 3.7(s/0.018) + 3.8(s/0.018)^2 + (s/0.018)^3} \qquad (13)$$

(iii) For T_{ph} = 400 seconds

$$H(s) \sim \frac{5.9(s/0.015)}{1 + 5.9(s/0.015) + 4.7(s/0.015)^2 + (s/0.015)^3} \qquad (14)$$

Responses to a step change in course in the systems described by equations 12, 13 and 14 are shown in figure 2.

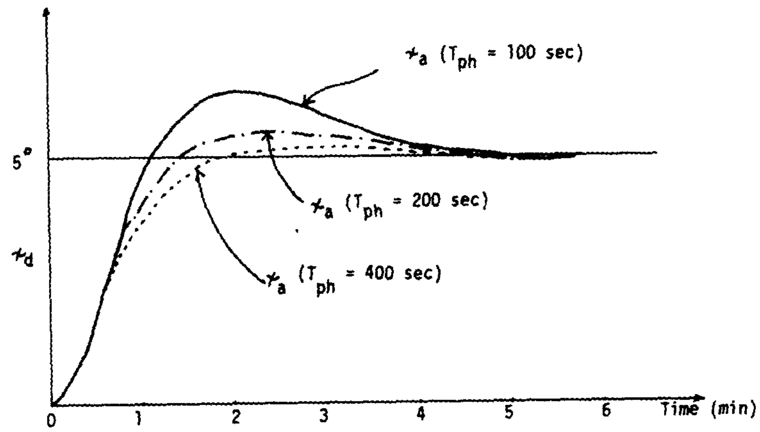

Fig. 2 Response to a Step Change in Course with I-Control

It can be seen in figure 2 that I-control (T_{ph}) has a significant effect on the system dynamic response. This actually offers us a wider choice for "optimum" setting of the autopilot parameters in accordance with different environmental, ship loading and speed conditions.

DIGITAL CONTROL ALGORITHM FOR MICROPROCESSOR BASED AUTOPILOT

The digital control algorithm implemented was based on the transfer function of the analogue alogrithm described by equation 5. The bilinear z-transform method was employed for the transformation of the continuous control algorithm into its digital equivalent, in a form suitable for implementation on a microcomputer. The relationship between s-domain and z-domain is approximated as:

$$s = \frac{2}{T} \left(\frac{1 - z^{-1}}{1 + z^{-1}} \right) \qquad (15)$$

where T is the sampling time.

Substituting for s into equation 5, we have:

$$\frac{\psi_d}{\psi_e}(z) = \frac{K_r}{T_{ph}}\left\{\frac{T_{ph}[2(1 - z^{-1})] + T(1 + z^{-1})}{2(1 - z^{-1})}\right\}$$

$$\left\{\frac{T(1 + z^{-1}) + 2K_{cr}T_{cr}(1 - z^{-1})}{T(1 + z^{-1}) + 2T_{cr}(1 - z^{-1})}\right\} \qquad (16)$$

After further derivation, equation 16 can be represented in a difference equation as:

$$\delta_d(n) = \frac{1}{A_1}\,[A\psi_e(n) + B\psi_e(n_{-1}) + C\psi_e(n_{-2})$$

$$+ B_1\delta_d(n_{-1}) + C_1\delta_d(n_{-2})] \qquad (17)$$

where $A_1 = (T + 2T_{cr})$

$B_1 = (4T_{cr})$

$C_1 = (T - 2T_{cr})$

$$A = \left\{K_r[2K_{cr}T_{cr} + T + \frac{T(T + 2K_{cr}T_{cr})}{2T_{ph}}]\right\}$$

$$B = \left\{K_r[\frac{T^2}{T_{ph}} - 4K_{cr}T_{cr}]\right\}$$

$$C = \left\{K_r[2K_{cr}T_{cr} - T + \frac{T(T - 2K_{cr}T_{cr})}{2T_{ph}}]\right\}$$

The digital algorithm of the autopilot was implemented on a Rockwell AIM-65 microcomputer system and programmed in BASIC. The controller unit was completed by adding an ADC (0804) and a DAC (ZN425E). (figure 3).

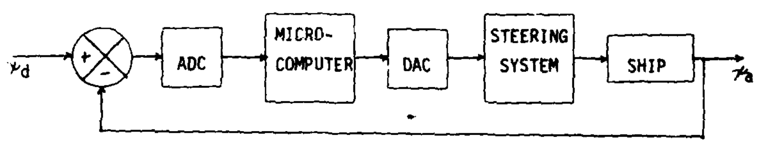

Fig. 3 A Microprocessor Based Steering Control System

It has to be noted that both the ADC and DAC employed are unsigned, i.e. they only operate over a positive range. However, the error signal from the comparator may be positive or negative, a positive bias is therefore required at the input end of the ADC to ensure correct phase operation. Similarly, a negative bias is required at the output end of the DAC to maintain the original polarity.

The software included the implementation of the developed digital algorithm on the microcomputer and the handling of the input/output operation between the microcomputer and the outside world. Unlike at assembly or machine language levels where the prospective user must be familiar with the whole memory map for that particular microcomputer, we need only to know the details of the I/O memory map to use BASIC. Further details of the hardware and software design can be found in [19].

STEERING RESPONSE ANALYSIS

A series of dynamic tests were performed on the microprocessor based autopilot and its performance compared with its analogue counterpart. Parameter settings for the control algorithm were based on the ones derived through the standard-model-matching approach. The effect of employing different sampling rates and the performance of the autopilot under different conditions of sea and windage were also investigated.

Effects of Sampling Rates

Besides the parameters of the control algorithm, sampling rate is also a critical factor in digital control. Neither too high nor too low a sampling rate is desirable. The choice of the sampling rate is usually based on 1/10 of the PU (period of critical oscillation), or 1/10 of the value of the smallest time constant of interest in the system.

With the "Mariner Class" of cargo vessel, PU was estimated to be 60 seconds [19]. The obvious choice for the sampling time was therefore 6 seconds. For comparison, sampling times of 10 and 2 seconds were employed, being 1/10 of the largest and about 1/10 of the smallest time constants of the transfer function (equation 4).

Tuning charts for the parameters settings are included in Table 1 to 3 for the three different sampling times. Dynamic responses to step changes in course demand (5 degrees starboard) are included in figures 4 to 7.

Table 1

$K_r = 0.35$ $K_{cr} = 4$ $T_{cr} = 25$ seconds

$A_1 = 56$ $B_1 = 100$ $C_1 = -44$ $T = 6$ seconds

T_{ph} (secs) / Parameter	100	200	400	∞
A	74.263	73.18	72.64	72.1
B	-139.874	-139.937	-139.968	-140
C	65.863	66.88	67.39	67.9

Table 2

$K_r = 0.35$ $K_{cr} = 4$ $T_{cr} = 25$ seconds

$A_1 = 60$ $B_1 = 100$ $C_1 = -40$ $T = 10$ seconds

T_{ph} (secs) Parameter	100	200	400	∞
A	77.175	75.34	74.4	73.5
B	-139.65	-139.825	-139.9	-140
C	63.175	64.84	65.67	66.5

Table 3

$K_r = 0.35$ $K_{cr} = 4$ $T_{cr} = 25$ seconds

$A_1 = 52$ $B_1 = 100$ $C_1 = -48$ $T = 2$ seconds

T_{ph} (secs) Parameter	100	200	400	∞
A	71.4	71	70.88	70.7
B	-139.986	-139.99	-140	-140
C	68.6	68.95	69.13	69.3

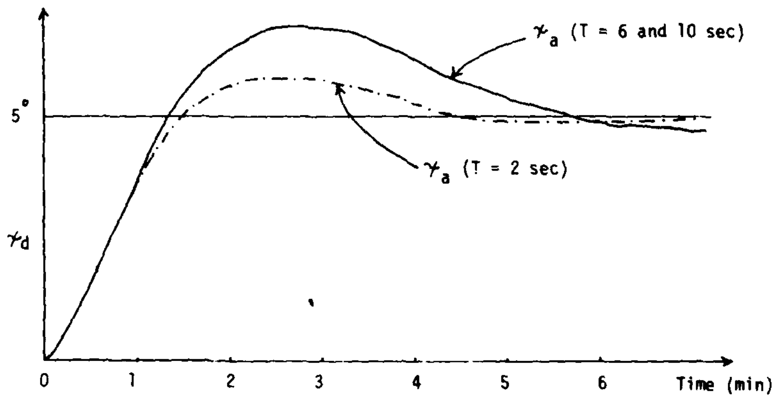

Fig 4. Responses with T_{ph} Equals 100 sec (T = 2, 6 and 10 sec)

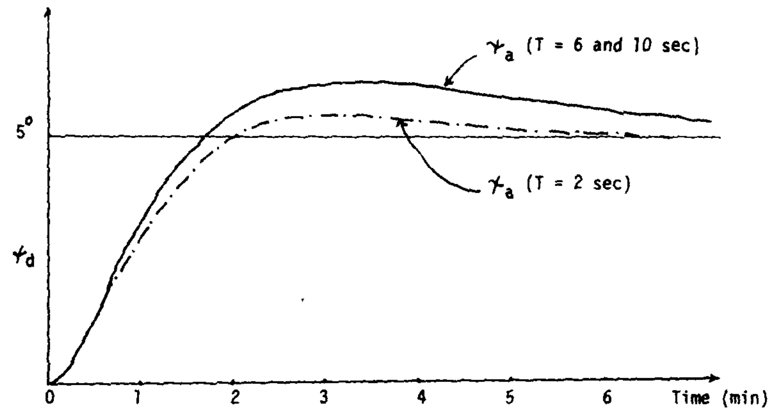

Fig. 5. Responses with T_{ph} Equals 200 sec (T = 2, 6 and 10 sec)

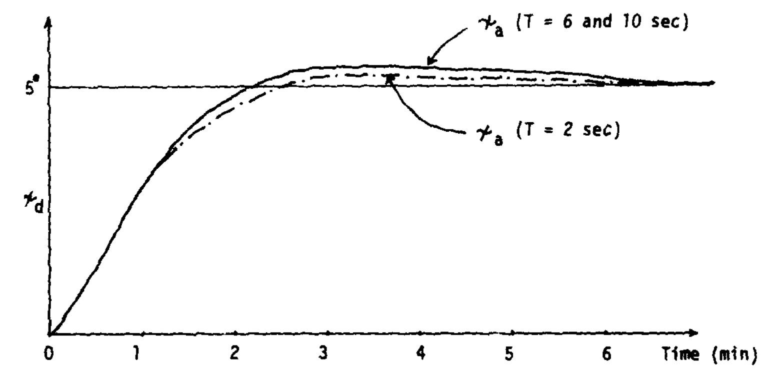

Fig. 6. Responses with T_{ph} Equals 400 sec (T = 2, 6 and 10 sec)

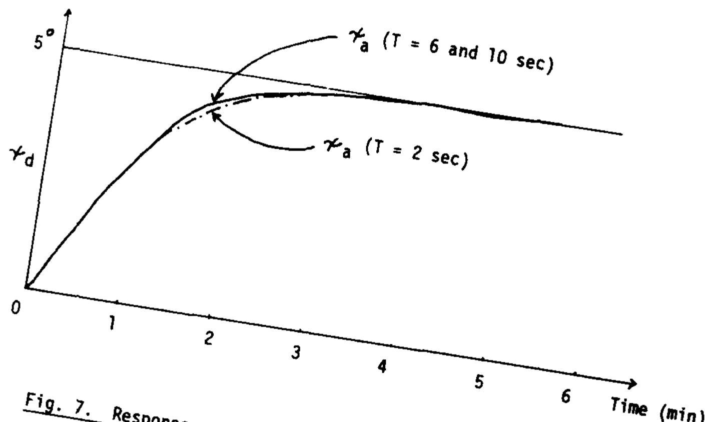

Fig. 7. Responses with T_{ph} Equals ∞ (T = 2, 6 and 10 sec)

With reference to figures 4 to 7, it can be seen that with the sampling time T set at 6 seconds the response for all values of permanent helm (T_{ph}) is closely matched with those for T = 10 seconds. With T equal to 2 seconds, there is a lag in rising time and less overshoot, signifying fewer integral actions in the control systems. The differences in the responses for the three different settings of T are more pronounced with T_{ph} equal to 100 seconds (figure 4), and these differences decrease as the value of T_{ph} increases. The responses more or less coincide when $T_{ph} \to \infty$ (figure 7). Further variation in the values of T provided the following results:

1. Decreasing T from 2 seconds further diminished integral actions, until instability occurred with T = 0.5 seconds.
2. Reasonable responses were obtained with increases in T up to 15 seconds. A significantly larger overshoot was detected with T = 20 seconds and with T_{ph} = 100 seconds; although with higher values of T_{ph}, this effect was diminished. Any further increase in T, besides lengthening the initial delay time (which is undesirable), further de-stabilised the system. With T equal to 30 seconds, a 45 percent overshoot resulted, and with T = 50 seconds this rose to over 80 percent.

Comparison of Digital and Analogue Autopilots

Responses of the microprocessor based autopilot ship steering system are shown in figures 8 to 11. The different graphs show the responses with permanent helm (T_{ph}) set at 100, 200, 400 seconds and ∞, and a sampling time of 6 seconds. Responses of the analogue autopilot are plotted on the same figures for comparison. The closed-loop transfer functions of the above systems are described by equations 9, 12, 13 and 14.

With reference to figures 8 to 11, it can be seen that there is a time lag between the digital and analogue responses. This is better demonstated by comparing the outputs of the two autopilots, along with the rudder response (figure 12).

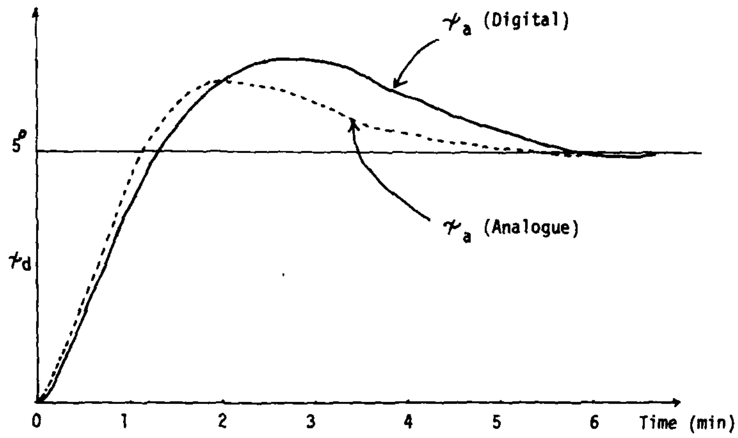

Fig. 8. Responses of Digital/Analogue Autopilots (T_{ph} = 100 sec)

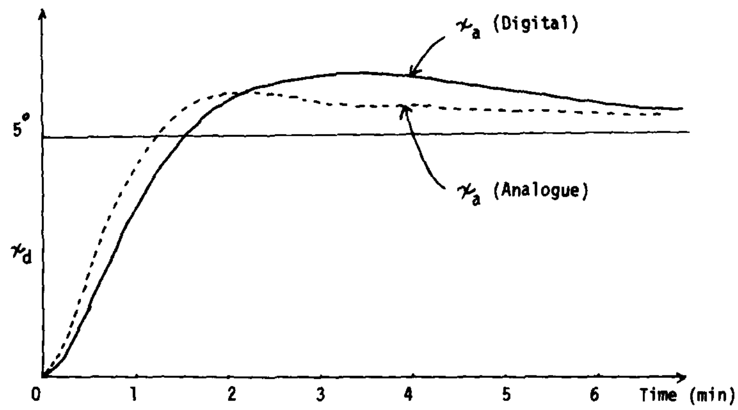

Fig. 9. Responses of Digital/Analogue Autopilots (T_{ph} = 200 sec)

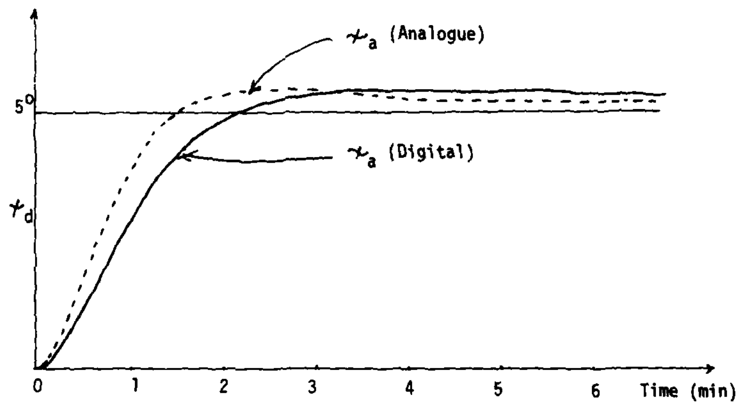

Fig. 10. Responses of Digital/Analogue Autopilots (T_{ph} = 400 sec)

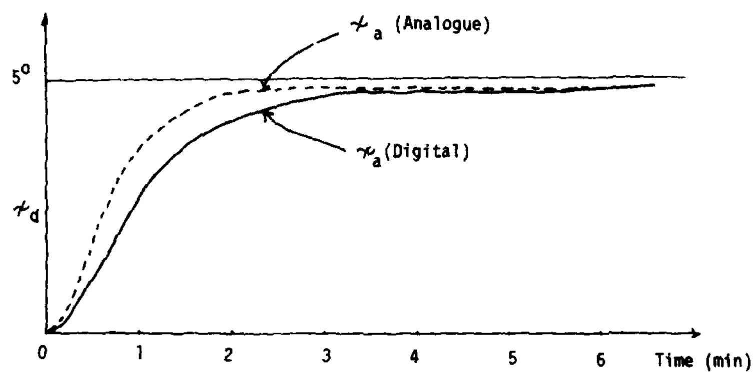

Fig. 11. Responses of Digital/Analogue Autopilots ($T_{ph} = \infty$)

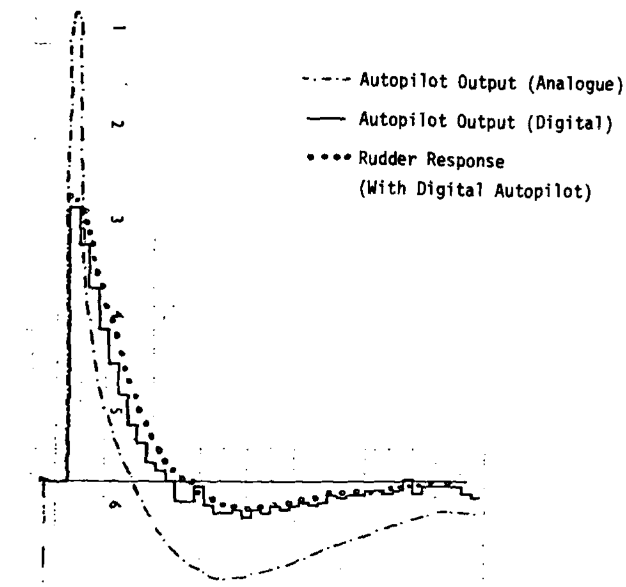

Fig. 12. Autopilot Outputs and Rudder Response ($T_{ph} = \infty$)

The main reason for the time lag is assumed to be the use of a fixed sampling time for the iteration process in digital systems. Apart from time lag, the shape of the responses of the digital control system match the standard data [24] more closely than as their analogue counterparts. This is due to the fact that the microprocessor based autopilot can handle the exact value of the parameter settings, while approximate settings have to be made with the analogue autopilot.

Performance of the Autopilots Under Disturbances

In order to study the performance of a ship steering control system in a more realistic manner, environmental factors have to be taken into account. Simulation of sea/wind disturbances should therefore be included. However, an accurate description of the various forces and moments experienced by a ship in open waters requires a complex analysis of waves and other physical phenomena along with a study of ship/sea interaction, involving both hydrodynamic and hydrostatic effects [25]. In an effort to simplify such analysis, a spectral approach was adopted for this study. This is suggested by the obvious features of irregularity and the random nature of the sea-state even under comparatively calm conditions. The approach employs filters with transfer functions closely resembling the shape of the wave height spectrum; when excited by white noise, the filters produce an irregular sea model output.

Investigations into the performances of the autopilot under the simulated Beaufort sea states "3" and "8" were carried out. Responses of the system with the digital autopilot incorporating permanent helm values of 100, 200 and 400 seconds are shown figures 13 and 14.

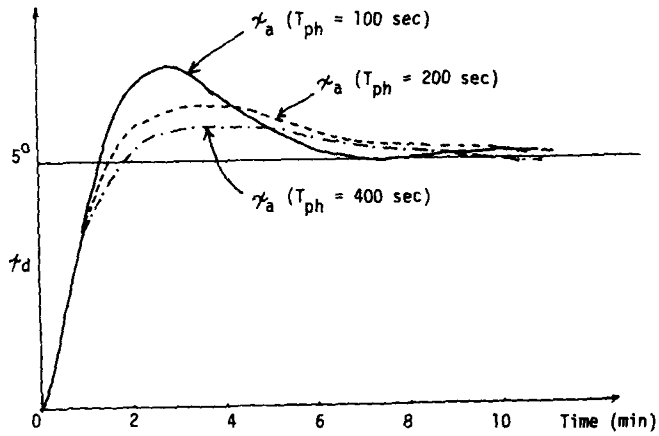

Fig. 13. Performance of Digital Autopilot Under Sea/Wind State "3"

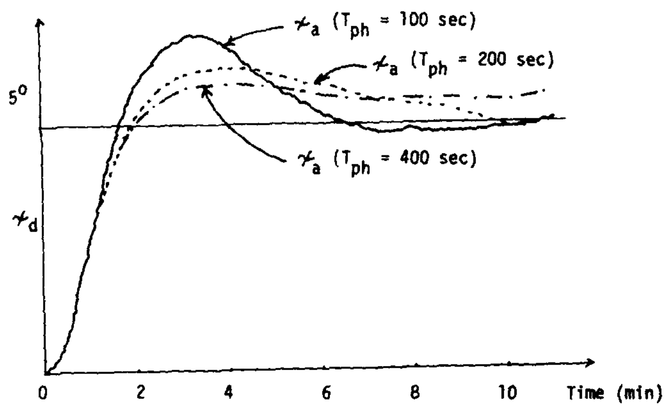

Fig. 14. Performance of Digital Autopilot Under Sea/Wind State "8"

The above figures illustrate the effect of permanent helm (T_{ph}) under conditions of sea/wind disturbances, and demonstrate its importance under such conditions. It can be seen that under sea/wind state "3", a longer integral time constant is preferable (e.g. 400 seconds). In such cases, a smaller overshoot with reasonable settling time is achieved. However, when the ship is under sea/wind state "8", a shorter integral time constant is required (e.g. 100 or 200 seconds). Otherwise, there will be a large course off-set. The foregoing results show that the performance of the microprocessor based autopilot, under sea/wind disturbances, is at least broadly comparable with that of an analogue system. The performance of the analogue autopilot under the same external influences is shown in figures 15 and 16.

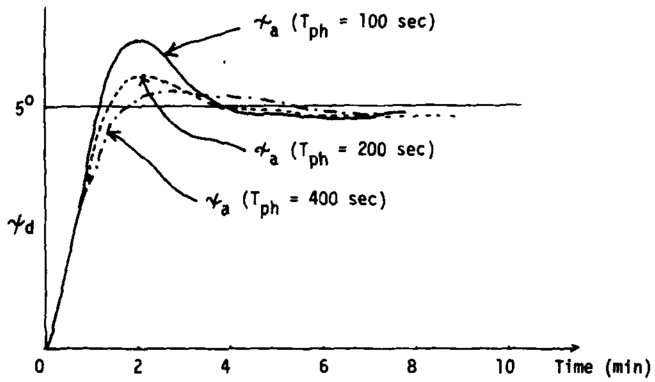

Fig. 15. Performance of Analogue Autopilot Under Sea/Wind State "3"

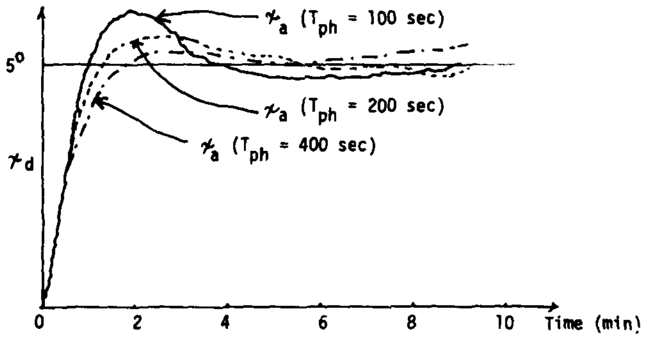

Fig. 16. Performance of Analogue Autopilot Under Sea/Wind State "8"

CONCLUSIONS

It has become clear that the classical approach to controller design can be used as a basis for the design of digital autopilot when using the bilinear z-transform method of converting an analogue algorithm to a digital one. This method, based on approximate integration where the sampling time T is a critical factor in the control system design, cannot tolerate either too high or too low a sampling rate. In most cases, the iteration involved in this method leads to a time lag between the analogue and digital system responses. With reference to the autopilot ship control system, this time lag would not impose any serious operational problems. In fact, such delay could offer the beneficial effect of additional damping which is particularly desirable when the ship is under small oscillatory influences.

The PID algorithm is generally accepted as being adequate for most control systems, however, the main drawback of the conventional PID autopilot for marine applications is the lack of adaptability. A microprocessor based PID autopilot can provide such adaptability to changes in environmental conditions and in ship dynamics. The parameters of the digital control algorithm can be tuned automatically to adapt to new situations. In addition, microprocessor based system allows more accurate parameter setting than its analogue counterpart, and in certain cases, more accurate responses can be achieved by the digital autopilot.

Optimisation of a ship steering system has not yet been perfected but the standard-model-matching method investigated is believed to be a reasonable approach to the problem. One benefit of this approach is the existence of standard data (for second order or third order coefficient plane models) which can be used to evaluate the standard of the responses.

An 8-bit microcomputer with 8-bit ADC and DAC was employed for this study. However, for greater accuracy, 12-bit or 16-bit ADC and DAC should be used. As regards the parameter setting of the digital control algorithm, figures of at least 4 significant digits are required. Floating point arithmetic was employed, largely for this reason, the BASIC language was used in this study, in preference to machine code, for ease of programming. Because the ship steering system is a relatively slow process, time lapse between the output and input of the digital controller is not a critical problem.

Through dynamic testing, it was shown that the microprocessor based autopilot performed satisfactorily as compared with its analogue counterpart. However, the above experiments were based on a simplified ship model and steering systems. The effects of non-linearity and unstable ships have not been dealt with. The practical value of the above design for actual ships has therefore still to be investigated.

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MODEL TESTS AND FULL-SCALE TRIALS
WITH A RUDDER ROLL STABILIZATION SYSTEM

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ABSTRACT

After a few earlier attempts, a renewed interest has recently arisen in rudder-roll stabilisation (RRS) systems. It appears to be possible to use the rudder simultaneously for the control of yaw and roll. The RRS project at Delft University of Technology was started in 1981 with a series of full-scale experiments, which resulted in a mathematical model describing the transfer between the rudder and the yaw and roll motions. The model was subsequently used to design a :on-roller. The controller was extensively tested with digital computer simulations, scale-model experiments in open water and full-scale trials with a ship of the Royal Netherlands Navy. The experiments demonstrated that an RRS autopilot is able to realise roll reduction comparable to that achieved by fin stabilisers. This paper reports the results of these experiments.

1. INTRODUCTION

Recently the idea of stabilising a ship by means of the rudder has received renewed interest. Searching through the proceedings of former ship control systems symposia, we found publications on this subject in the symposia of 1972 (Cowley and Lambert) and 1975 (Cowley and Lambert, Carley, Lloyd). In 1978 there were no papers on Rudder Roll Stabilisation (RRS) and the idea seemed to have been forgotten.
In 1980, however, Baitis reported successful trials with an RRS-system combined with manual control of the heading. At the SCSS in 1981 Van Amerongen and Van Cappelle described a simple mathematical model which can be used as a basis for the design of an RRS-controller. In the paper of Kallstrom (1981) the idea of RRS was also mentioned.

The present paper describes the progress made since 1981 at the Control Laboratory of Delft University. The main emphasis is placed or the results obtained. At Delft University the research on the RRS project is carried out in close cooperation with the company Van Rietschoten & Houwens and with the Royal Netherlands Navy. The Navy is considering application of the RRS autopilot described in this paper to the new M-class frigates.

The paper is organised as follows: Section 2 describes the mathematical models which are used to design the controller. Section 3 describes the controller design. Section 4 gives the results of simulation experiments. Section 5 deals with the trials carried out with an 8 metre long scale model on open water. Full-scale trials at sea with a naval ship are treated in Section 6. Finally, Section 7 summarises the conclusions and indicates future developments.

2. MATHEMATICAL MODELLING

The motions of a ship in waves depend on

- the dynamics of the ship,
- the disturbances, and
- the controller output, which is influenced by the steering machine.

The ship's dynamics

The basic equations which describe the motions of a ship can be derived from hydrodynamics. Full-scale trials (See Van Amerongen and Van Cappelle, 1981) indicate that a good description of these motions is obtained by the model of figure 1.

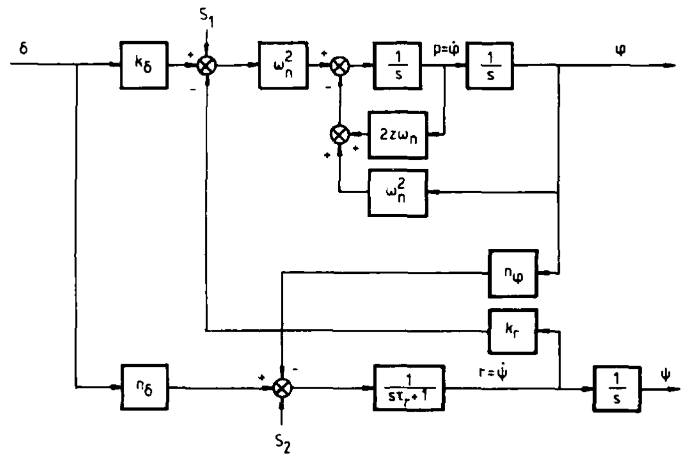

Fig. 1 Simplified dynamics between rudder and yaw and roll.

In this figure δ is the rudder angle,
ϕ is the roll angle,
and ψ is the heading angle.

It should be noted that the transfer from rudder to roll has a non-minimum phase character. A typical response is given in figure 2. For reduction of the roll angle only high-frequency rudder motions can be applied. Low-frequency rudder motions not only cause yaw, but also have the opposite effect on roll than high-frequency rudder motions do. This can be clearly seen in figure 2.

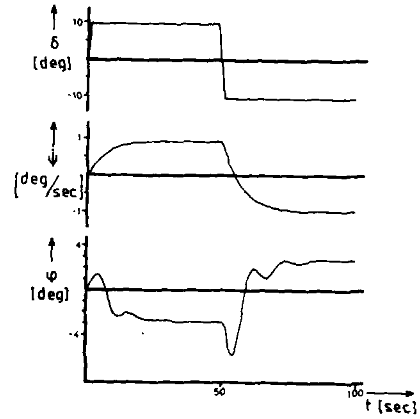

Fig. 2 Response of the rudder-roll transfer.

The disturbances

Waves are the most important disturbance with respect to roll. They can be described by means of a frequency spectrum, for instance the Bretschneider spectrum, recommended by the 12th ITTC (See, for instance, Bhattacharyya, 1978):

$$S(\omega) = \frac{691}{\bar{T}^4 . \omega^5} \left(\frac{H_{1/3}}{2}\right)^2 . \exp\left(\frac{-691}{\bar{T}^4 . \omega^4}\right) \; m^2 s \qquad (1)$$

where $\bar{T}$ is the average period

and $H_{1/3}$ is the significant height of the waves.

Figure 3 gives some typical examples for various wind speeds. The disturbance signals which can be computed on the basis of these spectra can be added to the model of figure 1, as indicated in that figure.

The steering machine

For the purpose of this paper the steering machine is sufficiently accurately described by the block diagram of figure 4. When the rudder is going to be used for reduction of the roll motions it should be able to follow frequencies of about $\omega = 0.6$ rad/s without a noticeable phase lag. This demand puts restrictions on either the maximum rudder angle or the maximum rudder speed. The latter is determined by the construction of the steering machine and the number of hydraulic pumps. It can easily be seen that for a sinusoidal motion

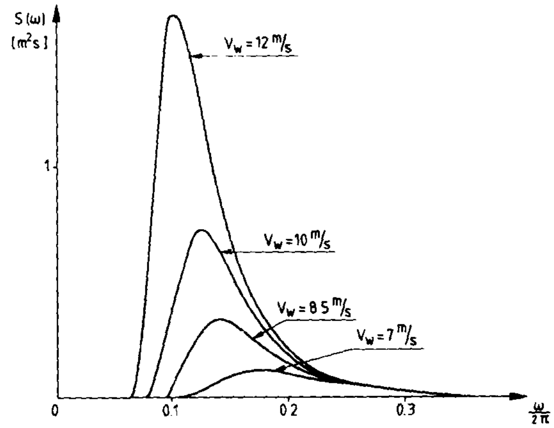

Fig. 3 Wave spectra.

$$\delta_r = \delta_{max}\sin(\omega t) \tag{2}$$

and $$\dot{\delta}_r = \omega\delta_{max}\cos(\ t) \tag{3}$$

The maximum frequency which can be followed without distortion of the signal is thus

$$\omega = \frac{\dot{\delta}_{max}}{\delta_{max}} \tag{4}$$

In the controller design care must be taken to ensure that the maximum rudder angles be limited as a function of the frequency of the rudder signal in order to prevent phase lag. The problem can be simplified by choosing a fixed value of the maximum frequency and setting:

$$\delta_{max} = \frac{\dot{\delta}_{max}}{\delta_{max}} \tag{5}$$

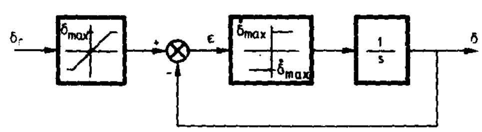

Fig. 4 Simplified model of the steering machine.

3. CONTROLLER DESIGN

3.1 Decoupling of yaw and roll

At present, active stabilising fins are most commonly used for roll reduction. They can be added to the model of figure 1 as an input parallel to the rudder input. In general, fins influence both yaw and roll, just as the rudder does. This yields a multivariable system with two inputs and two outputs. It has been demonstrated that it is advantageous to pay attention to the coupling between yaw and roll, either by designing a multivariable controller which decouples both motions (Freeman, Whalley and Waugh, 1982) or by applying optimisation methods (Kallstrom, 1981). In present controller designs the interaction is generally disregarded. This demonstrates that acceptable results may be obtained by controllers which do not explicitly take into account this interaction.
Because in a rudder-roll stabilisation system only one input (the rudder) is available to control two outputs, it is essential here that the interaction of yaw and roll be taken into account. Decoupling of yaw and roll can be obtained by restricting low-frequency rudder motions to control yaw while high-frequency rudder motions are restricted to roll reduction. The latter is also necessary due to the non-minimum phase character of the roll response which was mentioned in Section 2. The design of appropriate filters is an essential part of the controller design:

- a low-pass filter has to be designed to estimate the low-frequency components of the yaw motion, and

- a high-pass filter has to be designed to estimate the high-frequency components of the roll motion.

3.2 Estimation of the heading and rate of turn

The compass yields measurements of the heading. In general, the noisy character of this signal is mainly due to the disturbances of the waves, rather than to measuring errors. It has been demonstrated (Van Amerongen, 1982, 1984) that for optimal course keeping it is advantageous to suppress the high-frequency components of the heading measurements, because they lead to useless, high-frequency rudder motions. In order to minimise the phase lag, an adaptive state estimator has been designed (Van Amerongen, 1982, 1984) which yields low-frequency estimates of the heading and rate-of-turn signals. This estimator, which combines ideas of model-reference adaptive systems (MRAS) and Kalman filtering, is suitable for application in an RRS autopilot as well.

3.3 Estimation of roll angle and roll rate

In general, the roll angle will contain a constant offset which depends on how well the ship has been trimmed and on the disturbing moment of the wind. Because a constant roll angle cannot be reduced by RRS the controller should disregard it. Basically, a simple high-pass filter is suitable for this purpose.

When only measurements of the roll angle itself are available the roll rate, and eventually the roll acceleration, have to be estimated. How this can be done by means of Kalman filtering techniques is described by Van Amerongen, Hoogenraad and Van Nauta Lemke (1984).

3.4 The controller

The first attempt to design a controller uses LQ-design based on the dynamics of the model of figure 1 and on the criterion

$$J = \int_0^\infty (\underline{x}^T Q \underline{x}^T + \underline{u}^T R \underline{u})\,dt \tag{6}$$

with $\underline{x}^T = (\phi, \dot{\phi}, \psi, \dot{\psi})$

and $\underline{u} = \delta$

In general, the weighting factors in the criterion are chosen rather arbitrarily. Therefore, the designed controller can be further improved, in terms of bandwidth and damping ratio, for instance, by applying root-locus techniques for variations in the different controller gains.

However, it is even more important to add to the system the influence of the steering machine. Because this makes the system essentially non-linear, linear design methods are no longer applicable. The interactive design package PSI (Van den Bosch, 1981; Van Amerongen and Van den Bosch, 1984) which has been developed at Delft's Control Laboratory enables optimisation of a controller to be carried out for arbitrary systems and arbitrary criteria. It makes use of fast hill-climbing algorithms. With the aid of PSI, the controller has been redesigned for the total system. The values of the controller gains found with the LQ optimisation can be used as suitable starting values. Instead of criterion (6) following criterion has been used during PSI-optimisation:

$$J = 2.\max|\phi| + 5.\max|\psi| \quad \text{for } 0 < t > T \tag{7}$$

where $\max|\phi|$ and $\max|\psi|$ are the maximum values of the roll and heading signals during the observed time interval T. As a direct means of judging the roll-reduction performance a suitable criterion is

$$J = [\,1 - \frac{\sigma^2_{\phi,\ \text{closed}}}{\sigma^2_{\phi,\ \text{open}}}\,] \tag{8}$$

where $\sigma^2_\phi = (\phi - \bar{\phi})^2$

and ϕ_{open} is the roll angle without a controller and ϕ_{closed} is the roll angle with a controller.

This optimisation procedure yields fixed gains for each ship speed and disturbance. The influence of the disturbance on the motions of the ship depends not only on the spectra given but also on the angle of incidence of the waves. The latter not only affects the amplitude of the motions but also causes a frequency shift. Therefore it is essential that the controller parameters be adjusted by an adaptation

The first run of each series was made with the RRS controller switched off. This yields a reference for the other runs. Three different rudder speeds and maximum rudder angles were selected:

$\dot{\delta}_{max}$ - δ_{max} = 6 deg/s. - 10 degrees
$\dot{\delta}_{max}$ - δ_{max} = 15 deg/s. - 20 degrees
$\dot{\delta}_{max}$ - δ_{max} = 20 deg/s. - 30 degrees

In each situation the controller gains were selected as optimally computed before (nominal), 30 percent higher (+ nominal) and 30 percent lower (- nominal) in order to investigate the sensitivity to variations in the controller gains. The signals ψ, $\dot{\psi}$ and δ were obtained by means of the adaptive state estimator with the noise-suppressing properties described in Section 3. Most runs were made with sea state 6, and a few with sea state 6. This corresponds to wind forces of Beaufort 8 and Beaufort 10.
Figure 6 gives some typical examples. In figure 6a the angle of incidence is 60 degrees, in figure 6b 90 degrees and in figure 6c 120 degrees. A rudder speed of 15 degrees per second is used. The first part of each run is carried out without stabilisation, and the second part with stabilisation. The roll angle ϕ, the heading ψ and the rudder angle δ are shown.
Criterion (8) was used to compare the various runs. The results are summarised in figure 7, which gives the reductions for various angles of incidence as a function of the maximum rudder speed. Controller gains were made 30 percent higher and lower than the optimum values computed in advance, in order to investigate the sensitivity of the system to variations in the controller gains. All runs were successful except for those with a rudder speed of 20 deg/s, where the controller gains were apparently too high.

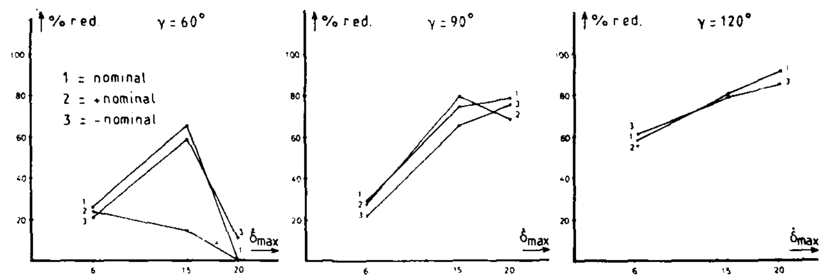

Fig. 7 Comparison of the controller performance with different angles of incidence and different rudder speeds.

The experiments indicate that the rudder speed in particular is an important parameter which determines the maximally achievable roll reduction. Rudder speeds which are common at present (3 to 7 deg/s) are generally too slow. A rudder speed of 15 deg/s appears to yield a considerable improvement. The variations made in the controller parameters indicate that the system is rather sensitive to these parameters. Settings which are too low are preferable to those which are too high, which may cause instability.

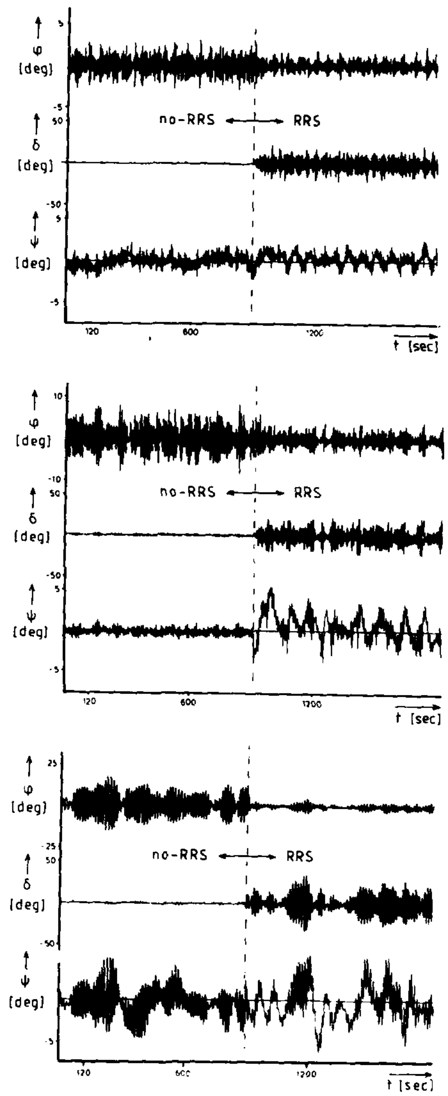

Fig. 6 Result of simulation.

5. MODEL TESTS

The next series of trials were carried out with an 8 metre-long ale model of the same naval ship used during the simulations. The ›del must be as large as possible in order to reduce the influence of scaling effects. Figure 8 gives an impression of this model.

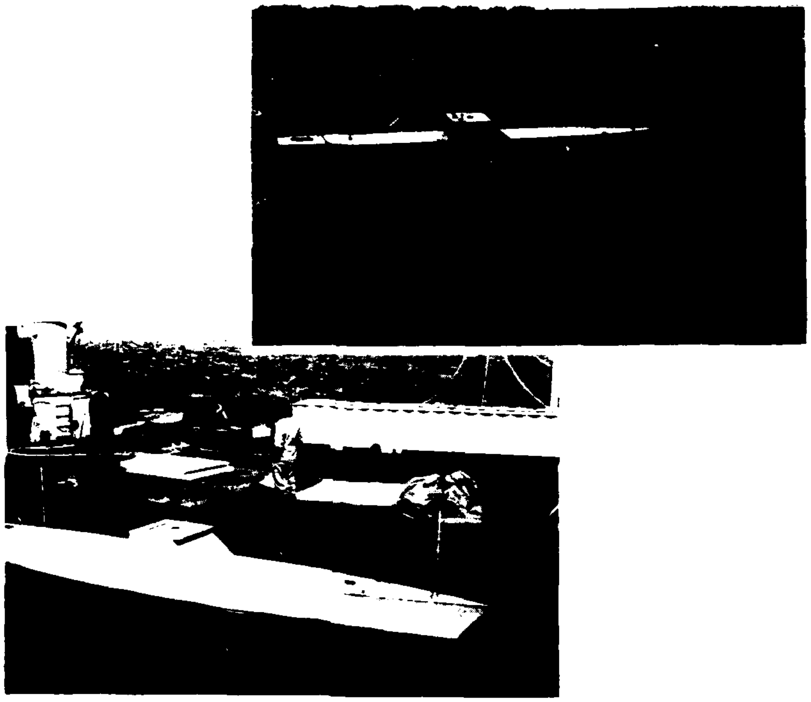

Fig. 8 Impression of the scale model.

Such a large model does not allow the planned type of trials to be carried out in a towing tank. Therefore, another solution had to be found. A location at the Haringvliet (a former sea arm in the South West of the Netherlands) seemed suitable for the trials. There is sufficient space available, the distance from shore to shore being about 3 km, while a measurement post of the Royal Netherlands Navy was available to install the equipment. Furthermore, the waves were expected to represent sea waves scaled with respect to the model.

The model was propelled by a diesel engine and equipped with gyro's nd a speed log in order to measure yaw, yaw rate, roll, roll rate and the ship's speed. Radio-communication channels were used to send these data to the shore where the computer with the autopilot was installed.

The desired rudder angle as well as signals to control the diesel engine were transmitted from the shore to the ship. Figure 9 shows this set-up including the equipment used for data recording.

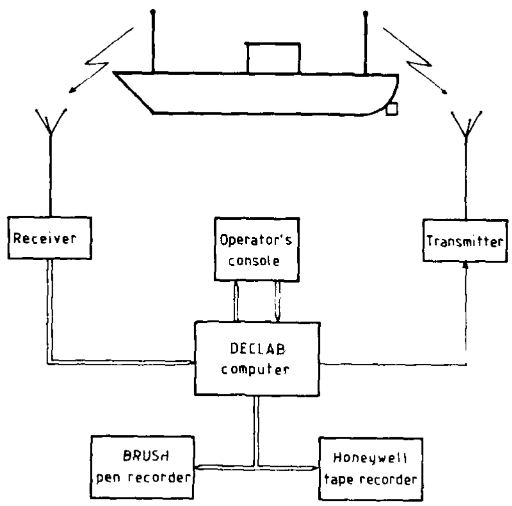

Fig. 9 Set-up of the measuring equipment.

The trials were carried out in co-operation with the NSMB, which equipped the model, and with the Ship Hydrodynamics Laboratory of Delft University of Technology, which took care of collecting the wave data. Because of the high sampling rate of the computer, necessary due to the time scaling, no computing time for data storage was available. Therefore, an additional analogue data recorder has been used.

One of the main problems of these trials was the continuously changing sea spectrum, and the variations of this spectrum, depending on the distance from the shore. Therefore it was difficult to make comparisons between one run and another. At moments when there was not enough wind to experiment with the RRS-controller, zig-zag trials were carried out for modelling purposes. The identification indicates that the mathematical models of the actual ship and the scale model did not completely match.

Only a few trials were carried out where good roll reduction could be demonstrated. But even the less successful experiments yielded valuable information for improving the controller design. It was demonstrated again that care should be taken to prevent the controller from generating signals which cannot be followed by the steering machine. In that case not only does the roll reduction deteriorate, but also significant heading errors occur. This phenomenon could also be observed in figure 6b and 6c. When the rudder angles become large, and high rudder speeds are required, too small a rudder speed causes low-frequency variations of the heading error.

These observations have led to the design of an important adaptive feature of the autopilot. As soon as it is detected that the demanded rudder speed exceeds the limitations of the steering machine, the ntroller is automatically adjusted. This reduces for some time the ll-reduction capability of the system as well, but it prevents the system from becoming unstable and it especially considerably improves the course-keeping performance.

This Automatic Gain Control (AGC) system, for which a patent is pending, has been added to the RRS controller and was tested during the full-scale trials described in the next section.

6. FULL-SCALE TRIALS

The main aim of the full-scale trials was to verify the earlier simulation results on a real ship and to test the AGC-system. The experiments were carried out on board a ship of the Royal Netherlands Navy, similar to the ship whose dynamics were simulated in the simulation experiments. Various rudder speeds were used In the simulations. During the full-scale trials the rudder speed was 7 deg/s. The experiments were carried out on the North Sea. The circumstances were almost ideal for these kind of trials: wind forces up to Beaufort 10.

During the trials experiments similar to those of the simulation experiments were carried out. Two ship speeds were used, 18 and 22 knots. As far as possible the angles of incidence of the waves were 60, 90 and 120 degrees, as defined in figure 5. Because the wind direction changed several times between the first and the last trials most of the time the waves were far from unidirectional.

ie performance of the Rudder-Roll-Stabilisation (RRS) controller was compared to that without any roll-reduction system and to the performance with the ship's fin-stabilizers on. During the runs where no RRS was used, the heading control was performed either by the ship's standard adaptive autopilot or by the adaptive autopilot (ASA) which is part of the RRS-controller. A description of the ASA autopilot is given by Van Amerongen (1982, 1984). In the following, runs with only control of heading and no roll reduction will be referred to as "open runs" while those with roll reduction will be called "closed runs". In principle every closed run is preceded and followed by an open run in order to be able to compare both types of runs under changing conditions.

The main difference with the formerly used controllers was the implementation of the above-mentioned automatic gain control (AGC) feature.

Figures 10,11,12 and 13 give the roll reductions obtained and course-keeping performance with the RRS controller during the whole period of the trials. The solid lines indicate the performance of the open system, and the dashed lines the performance of the closed system (the RRS controller). Results obtained with the fin-stabilisers are not given here. They will be discussed later. Note that

σ_{ϕ}^2 is the variance of the roll angle,

σ_{ψ}^2 is the variance of the heading error, and

γ is the angle of incidence of the waves as defined in figure 5.

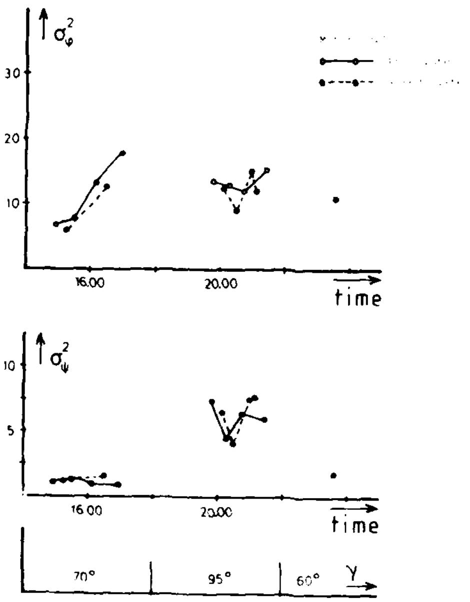

Fig. 10 Results of the trials on Monday

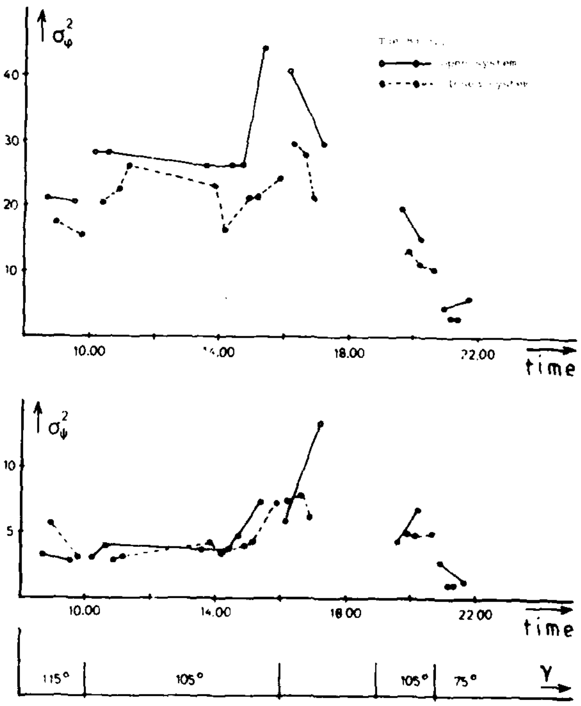

Fig. 11 Results of the trials on Tuesday

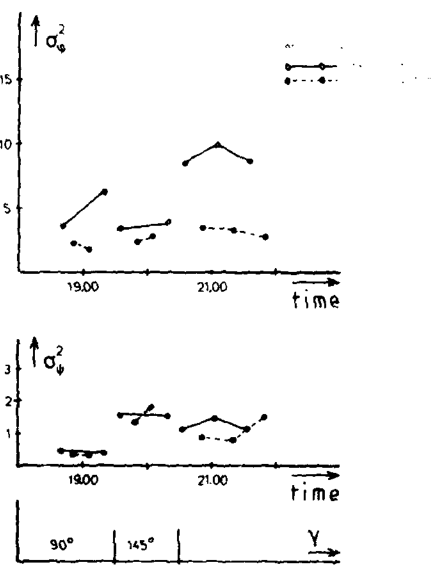

Fig. 12 Results of the trials on Wednesday

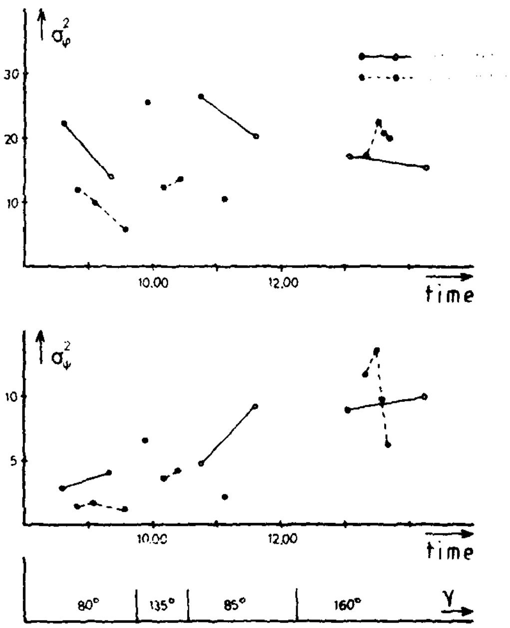

Fig. 13 Results of the trials on Thursday

The runs on Monday, March 21 do not show large reductions because this period was used to experimentally adjust a series of parameters (figure 10). Moreover, the authors had to adjust themselves to the motions of the ship. A maximum roll reduction of 27 % was realised. The roll reduction is measured by criterion (8). During these experiments the wind speed varied between 20 and 40 knots (Beaufort 6 - 8). During several squalls, even larger wind speeds were observed. The waves were approximately 4 metres high (sea state 5 - 6).

On Tuesday the maximum roll angles were larger than the day before (figure 11). The roll angles sometimes exceeded the limit of 20 degrees which was selected as a maximum. Due to this saturation the roll reduction deteriorated during a few runs. Therefore the scaling of the roll sensor was re-adjusted to a maximum of 30 degrees. The wind speed decreased from 45 knots (Beaufort 9) in the morning to 30 knots in the evening (Beaufort 7). Waves were 3 to 4 metres high (sea state 5). Roll reductions up to 44 % were obtained.
On Wednesday, March 23 the wind had decreased and the sea was much calmer (figure 12). No measurements were carried out during the day. In the evening the wind picked up (wind speeds greater than 25 knots). The waves were approximately 1.5 metres high (sea state 3). During this period the largest reductions were measured (over 60 %).

On Thursday the wave height had increased to 3 m. (sea state 4 to 5). Still, considerable reductions were obtained (more than 50 %, figure 12).

During several runs it was observed that the course-keeping performance was improved when the RRS-controller was used. This phenomenon was not further investigated but it has also been observed in simulation experiments of Kallstrom (1981).

During the afternoon trials were carried out with a ship's speed of 22 knots and following seas (γ = 160 deg.). No roll reduction could be measured. The variances with the RRS controller on were even larger than without RRS.

In figure 14 a qualitative comparison is given between ASA and two RRS controllers. ASA only controls the heading. RRS1 shows the performance of an RRS controller with controller gains that are too large. RRS2 is an RRS controller with controller gains which are well adjusted. The output of the automatic-gain-control system ("A") is plotted in this figure as well. Apparently it indicates how well adjusted the controller is. When the automatic-gain-control system responds only a few times (RRS2) better variances of all the signals are measured.

A comparison of ASA, the RRS-system and the ship's autopilot is given in figure 15. In this figure the roll reduction (64 %) is most cle. ly visible. The improved course-keeping performance of the RRS-controller can also clearly be seen, especially in comparison with the ship's autopilot. Another comparison between open and closed systems is made in figure 16.

This figure cle ly shows that almost all the runs give a positive roll reduction. .he few exceptions are indicated. The runs of the first day are indicated by the number 1. Because of the experimental character of these runs the reductions were small. The other series, indicated by the number 4 belongs to the last trials on Thursday where following seas combined with a ship's speed of 22 knots demonstrated

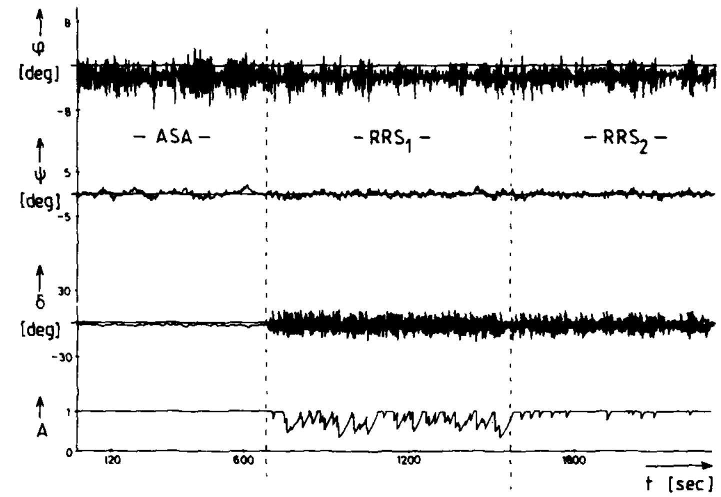

Fig. 14 A qualitative comparison between ASA and two RRS controllers.

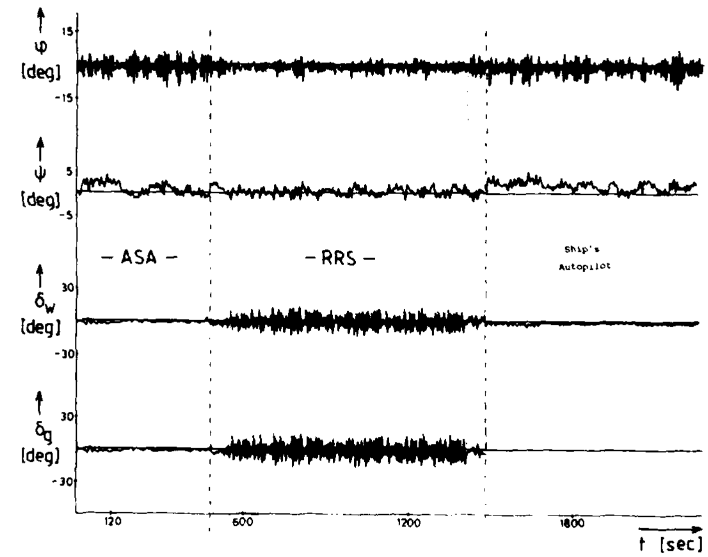

Fig. 15 A qualitative comparison between the ASA autopilot, an RRS controller and the ship's autopilot.

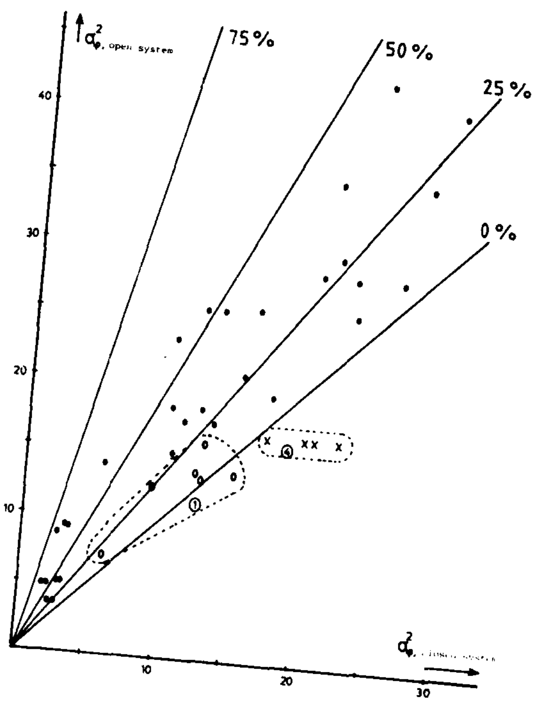

Fig. 16 Overview of the results of the full-scale trials.

the limitations of the RRS-controller. These results were already observed during simulation experiments and are now confirmed by the full-scale trials. This figure demonstrates that for large roll angles as well significant reductions (approximately 40 %) were measured. In judging these results it should be taken into account that the rudder of this ship has only a limited roll-reduction capability because of a relatively small rudder speed of 7 deg/s.

It is interesting to compare the results from the full-scale trials with the simulation results not only to validate the latter but also to extrapolate the simulation results for higher rudder speeds of the actual ship. In figure 17 the results of the experiments at the NSMB are summarised (cf. figure 7).

In this figure a series of reductions obtained during the full-scale trials, with a rudder speed of 7 deg/s has been added (plotted as X). Because it was not always possible to determine a unique wave direction, the frequency spectrum at sea was less sharp than during simulation. Furthermore, the angles of incidence of the waves do not completely match.
When these restrictions are kept in mind it seems allowable to make the comparison between the full-scale trials and the simulation

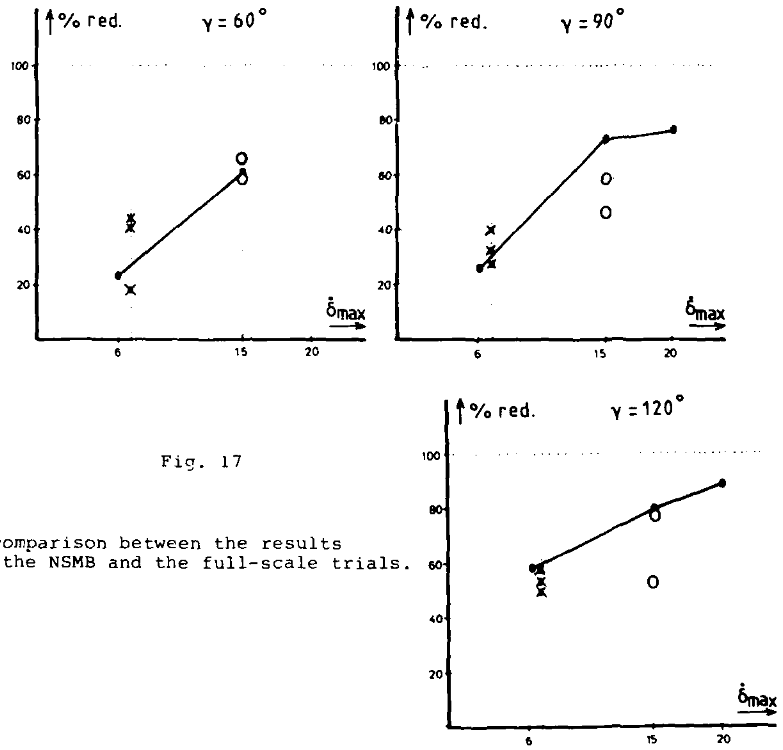

Fig. 17

A comparison between the results of the NSMB and the full-scale trials.

experiments. It can be observed that the reductions obtained at full scale are indeed comparable to those of the simulation.

In order to compare the present fin-stabiliser system to the reductions which may be anticipated for a maximum rudder speed of 15 deg/s, the reductions of the former have been added in figure 10 as well. They are plotted as open circles. It can be observed that the results of the present fin-stabiliser system are comparable to the simulation results of an RRS-system with a maximum rudder speed of about 10 to 15 deg/s. It may thus be expected that the roll reduction with RRS and a rudder of 15 deg/s will be at least as good as with present fin stabilisers.

7. CONCLUSIONS AND SUGGESTIONS

This report has demonstrated that a rudder-roll stabilisation system is able to realise roll reductions which are comparable to those which can be obtained by conventional systems based upon fins. Although the RRS system requires a more expensive steering machine (due to the higher rudder speed required and the heavier load) it is economically attractive. The expensive fin hydraulics and their control equipment are no longer necessary. Probably in addition the added resistance may be smaller (Van Amerongen and Van Cappelle, 1982).

The main conclusions which can be drawn from the various experiments are summarised below.

- RRS is able to realise considerable roll reduction, while maintaining a good course-keeping performance.

- It is essential that the rudder speed be increased. Extensive simulation experiments indicate that a rudder speed of about 15 deg/s is appropriate. From eqn (4) it can be deduced that, as a rule of thumb, the rudder speed should be equal to the maximally allowed rudder angle, multiplied by the ship's natural roll frequency.

$$\dot{\delta}_{max} = \delta_{max} \cdot \omega_n \tag{9}$$

- With a fast rudder, roll reductions comparable to those obtained with fins can be realised.

- In order to make the system less sensitive to small variations of the ship's parameters or changing sea states, the automatic gain control (AGC) described is essential. The AGC has also solved the problem of the deteriorating course keeping which was observed during the simulations and the scale-model tests.

- Other adaptive features should be added to the system. During the trials described in this paper all controller settings were adjusted manually. In particular the controller adjustment with respect to changing wave heights and direction has to be automated. This is the main subject of the present research.

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